# Mapping Freshwater Resilience

**in Alaska**

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**June 2025**

Center for Resilient Conservation Science

The Nature Conservancy

Please cite as:

Olivero, A.P., Barnett, A.R., Anderson, M.G., Khoury, M.L., and Martin, E.H. 2025. Mapping Freshwater Resilience in Alaska. The Nature Conservancy, Center for Resilient Conservation Science. Newburyport, MA.

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Funding for this project was provided by the TNC Catalyst Fund

*About the Cover*

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Title: Alaskan Autumn Colors
Alaskan wilderness in Denali, from the McKinley Explorer Train

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Title
Riding Bear-Back
Description
Riding Bear-Back // This Spring cub spent most of its time on momma brown bear's back, even when she was fishing. Most of the time the baby would fly off and tumble across the water when momma pounced on a fish, but would quickly climb back on. The salmon were plentiful in the river in Katmai National Park, Alaska.

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Title
WOPA100119_D025
Description
Aerial views of the Bristol Bay watershed in southwest Alaska, near the location of the proposed Pebble Mine. The Pebble Mine project is a large and controversial copper, gold, and molybdenum open pit mine proposed for develop within the watersheds draining into Bristol Bay. The Bristol Bay watershed lies within the region of Southwest Alaska, near Lake Iliamna and Lake Clark. An impact study is being conducted and supported by environmental groups, including the Nature Conservancy, to focus attention on the value of this fragile ecosystem and vital salmon spawning habitat.

# Dedication

Our colleague, Jonathan Higgins (1958-2022), contributed in so many ways to this work that we wanted to take this opportunity to acknowledge him and dedicate this work to him. From the beginning, he was a champion of mapping freshwater resilience, giving us sage advice to keep the model simple and grounded in the key attributes of freshwater ecosystems. While we are sure his blunt appraisal of our analysis would have improved it, we hope this work reflects his efforts to sharpen our critical thinking.

# Acknowledgments

We gratefully acknowledge The Nature Conservancy's Science Catalyst Fund for supporting this study and the endorsement of Toni Hardesty, Alison Cohan, Branden Bornemann, and Julia Nave that allowed us to go forward with it.

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CHAPTER

# Introduction 1

Freshwater species are the fastest declining, most endangered, species group in the U.S. Freshwater species are particularly vulnerable to climate change because they are confined to aquatic habitats, and their adaptive movement is sensitive to fragmentation by barriers. To address this, the Conservancy's Center for Resilient Conservation Science (CRCS) launched a project to identify and map a network of resilient rivers and streams which if conserved or restored could sustain the diversity of the conterminous U.S. freshwater ecosystems. Completed in 2024 (Anderson et al. 2024), this work is now being incorporated into a freshwater conservation vision for North America that will enable the U.S. Divisions to identify a pathway to TNC's 2030 goals that will have the greatest impact on sustaining freshwater diversity for nature and people.

**In this project, we expanded the freshwater resilience mapping to Alaska.** We compiled existing data and replicated the analyses of connectivity, condition, water alteration, and recognized biodiversity to complete a resilient and connected freshwater network for Alaska. The results identify many resilient river networks needing conservation as well as some vulnerable networks that could be restored to resilient through dam removal (reconnect), improved water quality or watershed land cover (restore condition), or improved hydrologic flow (restore flow). The results also provide information on the biodiversity value of each river network, allowing users to explore the intersection of biodiversity and climate resilience. Finally, we take stock of the conservation status and spatial distribution of current freshwater systems so that TNC can focus new conservation on systems that complement and enhance the existing set of conserved freshwater ecosystems.

## Background

Rivers, streams, lakes, ponds, wetlands, and springs are essential features of our landscape and history. Collectively, these freshwater ecosystems are critical to most life on earth and provide goods and services that support the livelihoods of billions of people (Russi et al. 2013). Fundamental services provided by freshwater biodiversity have been cataloged as material (food, health resources, goods), nonmaterial (educational and cultural values), and regulating (catchment integrity, water purification, and nutrient cycling) (Lynch et al. 2023). Covering less than one percent of the Earth's surface, rivers and lakes harbor at least 12 percent of the world's known animal species (Abramovitz 1996). In North America, freshwater ecosystems support 1,200 fish species that contribute to biodiversity, ecosystem productivity, human well-being, livelihoods, and prosperity (Burkhead 2012). Inland recreational fisheries, for example, generate more than $31 billion annually in the United States and Canada (DFO 2010; USFWS & USCB 2011).

The United States ranks first in fish diversity among all temperate countries (801 species), and first among the globe for diversity of crayfish (322), freshwater mussels (300), freshwater snails (600), stoneflies (600), and mayflies (590) (Master et al. 1998). Alaska also hosts a diversity of freshwater fish, including 52 freshwater or anadromous species sustained by the

state's extensive network of lakes, rivers, and streams (Alaska Freshwater Fish Inventory, 2024). Salmon, trout, char, grayling, and whitefish are prominent species.

Freshwater species are among the country's most threatened species group. Three decades ago, The Nature Conservancy (TNC), in cooperation with the state Natural Heritage Network released a species "report card" for the United States (Stein & Flack 1997) which found that:

- *"67 percent of U.S. freshwater mussels are vulnerable to extinction or are already extinct.*
- *More than 1 in 10 mussels may have become extinct during this century alone.*
- *303 fish species—37 percent of the U.S. freshwater fish fauna—are at risk of extinction.*
- *17 fish species have already gone extinct, mostly in this century.*
- *51 percent of U.S. crayfishes are imperiled or vulnerable.*
- *40 percent of amphibians are imperiled or vulnerable.*
- *At least 106 major populations of salmon and steelhead trout have been extirpated."*

Recent studies suggest that the situation has only worsened. A quarter of the world's 14,898 species of freshwater fish are now at risk of extinction according to the most recent International Union for Conservation of Nature assessment (IUCN 2023b). The IUCN study found that pollution from fertilizers and pesticides, sediment clogging up streams, and human sewage and industrial waste were the biggest threats, affecting 57% of the imperiled species. Dams and water extraction came in second, affecting 45% of threatened freshwater fish. Climate change compounds these threats. In drought-prone regions, water extractions reduce the absolute amount of freshwater available for other species, and dams and barriers hamper the ability of species to move to adjust to new climatic conditions (IUCN 2023a).

Alaska, the last largely pristine North American salmon-producing region, appears to have been an exception to the trend of freshwater decline but that may be changing. Of the 15 salmon populations currently listed as threatened, all are species that spawn on the West Coast of the conterminous US and occur in Alaskan waters only during the marine phase of their life. However, in 2024 NOAA indicated that listing for the one endemic species, the Gulf of Alaska Chinook salmon, was under investigation and may be warranted. Also in 2024, the commercial salmon harvest experienced significant declines in catch numbers and market value. The total harvest was the third lowest on record for total fish harvested and the lowest on record for total pounds harvested (Alaska Dept. of Fish & Game 2024). The well documented declines in Alaska's Pacific salmon size result primarily from shifting age structure associated with climate change and competition at sea and could result in substantial losses to ecosystems and people (Oke et al. 2020).

Freshwater fish are also vulnerable to changes in climate because they are confined to aquatic habitats, and movement to alternative habitats is often more restricted than in terrestrial systems (Lynch et al. 2016). Movement is further restricted when stream networks are fragmented by dams and barriers, but adaptive movement is a necessary behavior when aquatic species encounter changing climatic conditions. A nationwide study in France comparing electrofishing results from over 3,000 sites across four decades found systematic shifts in species distributions upstream and towards higher elevations (0.6 km upstream and 13.6 m in elevation per decade, Comte & Grenouillet 2013). Similarly, a 30-year survey of 1,500 lakes in Ontario Canada found sportfish range boundaries had shifted northward significantly at a rate of approximately 13-18 km per decade while baitfish had shifted

southward (Alofs et al. 2014). In marine environments, climate driven changes in species distributions and commercial fish stocks are well documented, and adjustments are being made in fisheries management (Karp et al. 2019). In Alaska, it has been confirmed that chum salmon are spawning in Arctic rivers on Alaska's North Slope, indicating a potential northward expansion of their range due to climate change (Westley 2023). In the conterminous U.S., the majority of streams and rivers (79% of stream length) are disconnected from their outlet (i.e., oceans and Great Lakes) which has contributed to the severe decline of many anadromous and potadromous species (Cooper et al. 2017) as species are now much more limited in their ability to move and access necessary habitats.

In the U.S., freshwater fish distributions are affected by contemporary climate change in ways consistent with anticipated responses under future climate scenarios. That is, the ranges of most coldwater species are shifting to higher altitudes or latitudes, whereas the ranges of cool and warmwater species are both expanding and contracting (Comte et al. 2013). Evidence for fish population movements in response to climate change is apparent in connected stream networks with wide temperature gradients such as the Bitterroot and Flathead rivers (Eby et al. 2014; Mulfeld et al. 2016) and the Great Lakes (Johnson & Evans 1990). In these systems, species are moving to track cooler temperatures and find suitable habitats or thermal refugia. Presumably, similar movements are also happening within smaller networks, but with more than 7,000 river dams fragmenting conterminous U.S. rivers and over 145,000 small dams preventing access to headwater streams (Anderson et al. 2024), such movements are increasingly a challenge.

Climate change may have other consequences for aquatic organisms because temperature and precipitation affect most of the physiological and geochemical processes that regulate their life history (Whitney et al. 2016). Evidence is beginning to accrue documenting phenological shifts in the timing of seasonal migrations or spawning, demographic changes in abundance, growth, and recruitment, and even evolutionary responses indicated by genetic change (Shanley and Albert 2014, Lynch et al. 2016, Shoen et al., 2023, Littell et al. 2023). In Alaska, stream networks are also experiencing high rates of change given the broader trend known as Arctic amplification (Holland and Landrum 2021, Li et al. 2024), leading to warming at more than twice the global average and related permafrost thawing, glacier melt, and changing weather patterns (Thoman et al. 2024, Mizukami et al. 2022, Michalek et al. 2025, Karjalainen et al. 2019). Although aquatic species have dealt with climate changes in the past, fragmented systems and restricted movement may hamper their ability to adjust to changing conditions. As Woodward et al. (2010) stated, “all organisms face the same options as the climate changes: adapt, migrate, or perish. However, an organism’s success in implementing the first two strategies will depend largely on its life history and dispersal traits in relation to habitat fragmentation and the rate at which its environment changes.”

# Approach

**Freshwater Resilience** *is the ability of a stream network or other aquatic setting to maintain biological diversity even as the system changes in composition and structure in response to changes in climate.*

Our approach to resilience was based on the idea of Conserving Nature's Stage (Beier et al. 2010). That is, we did not attempt to predict all the possible implications and interactions expected from climate change, but instead, we sought to identify and map the more enabling physical conditions that set the stage for aquatic species and assemblages to adapt to a changing climate with flexibility and integrity. We focused on mapping and evaluating the abiotic components of a freshwater network such as its length and diversity, the condition of its watershed and floodplain, its enduring access to surface water and groundwater, and the availability and alteration of its flow regime.

In our expansion of the freshwater resilience analysis to cover Alaska, we sought to use the same principles and where possible the same datasets as used in the CONUS assessment. Each dataset used in this Alaskan analysis covered the entire state of Alaska and in some cases extended into the Canadian lands draining into Alaska. Map products were evaluated and delivered for HUC-12 watersheds, a spatial resolution appropriate for informing local, regional, and national decisions.

# Mapping Freshwater Resilience

Our approach to mapping terrestrial resilience (Anderson et al. 2023, see https://www.maps.tnc.org/resilientland/) identified areas of high physical diversity and connectedness both locally and regionally, based on enduring features that provide species habitat options and the ability to move as the climate changes. This Conserving Nature's Stage approach (Beier et al. 2010; Anderson et al. 2014) recognizes that while the actors at any given site may change, we can focus conservation efforts on maintaining the diversity and ecological function of the stage.

Similarly, this freshwater resilience analysis identified characteristics that confer resilience for freshwater biodiversity in a changing climate. Our hypothesis for mapping freshwater resilience was that the physical setting and its condition, together with water availability and its alteration, drive resilience in freshwater systems by providing habitat options and the conditions to maintain ecological function. We used the term "functional connectivity" to refer to the contiguous portions of a river network available for a fish or aquatic organism to move through before they encounter a dam or other major anthropogenic barrier. The characteristics of this "functionally connected network" - its size, diversity, condition, and available water – determine its ability to support aquatic diversity under changing climates.

Our resulting “resilience score” estimates the relative capacity of a river network to maintain species diversity and ecological function as the climate changes. The building blocks of the resilience score are:

- Physical Score
    - Connectivity
    - Condition
- Water Score
    - Potential Water Availability
    - Flow Alteration

In our analysis, a resilience score is calculated for every HUC-12 watershed by integrating connectivity and condition into a physical score, integrating potential water availability and flow alteration into a water score, and finally integrating these two scores into an overall resilience score.

The factors that create resilience vary in importance with climate region. In the conterminous U.S., we adjusted the weight of each factor in the integration based on whether the river was in an arid or humid climatic region. Alaska’s climate is classified as non-arid (Zomer et al. 2022; Tabari 2020; Beck et al. 2018). The climate ranges from maritime in the southern portion of the state to continental in the interior, to arctic on the North Slope, but in no region does potential evapotranspiration exceed precipitation as in arid and semi-arid climates (Callegary et al. 2013; Zomer et al. 2022). Thus, we treated Alaska’s rivers similar to those in humid regions of the contiguous U.S., giving more weight to the physical score as the availability of water was not highly limiting.

CHAPTER

# Base Data & Analysis Units

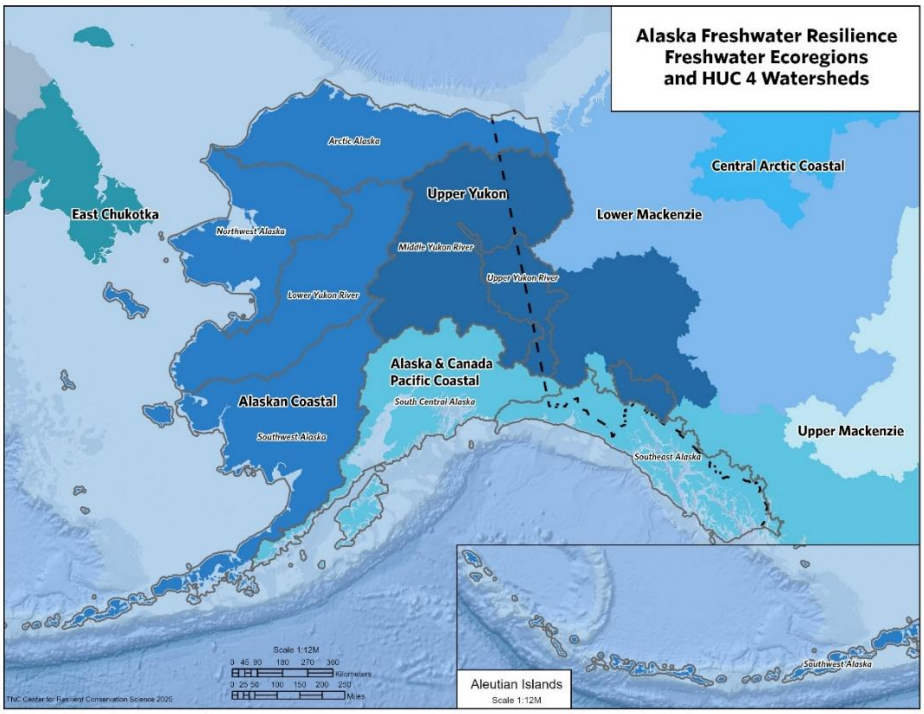
2

In this chapter, we describe the foundational datasets and analysis units that were used in the freshwater resilience analysis.

## Ecoregions

Alaska includes portions of three freshwater ecoregions and has eight major HUC-4 drainage basins which nest within these ecoregions (Figure 2.1). The watersheds separate naturally into those draining West and North to the coast, the large inland basin of the Upper Yukon, and the watersheds draining south to the Gulf of Alaska. The Alaska and Canada Pacific Coastal freshwater ecoregion contains temperate coastal rivers, while the Alaskan Coastal and Upper Yukon freshwater ecoregions are classified as polar freshwater systems. Peak flow in Arctic rivers occurs in spring and autumn, and is influenced by rain, as well as melting snow and ice. These rivers remain cool throughout the short summer, and freeze during winter, unless they are fed by perennial springs. Rivers south of the Arctic region have maximum flows between May and June, and may or may not freeze during winter, depending on their location and size. Most lakes are of glacial origin (Abell et al. 2008; WWF & TNC 2019).

**Figure 2-1. Freshwater ecoregions of Alaska.**

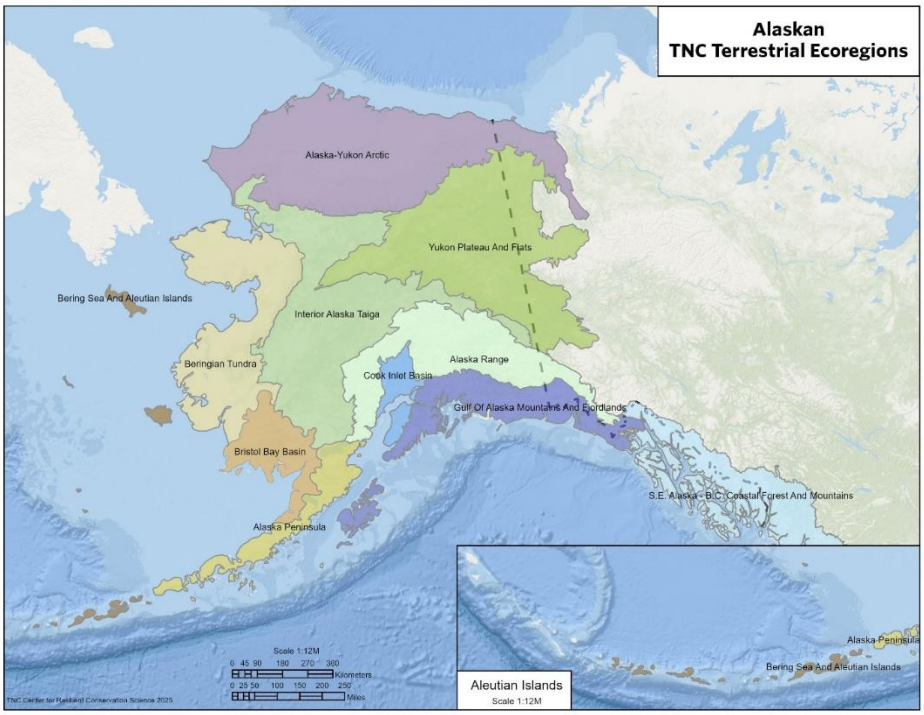


Terrestrial ecoregions are also used to describe differences in the freshwater and terrestrial ecosystems found in Alaska. The state contains portions of eleven major terrestrial ecoregions as used in the terrestrial resilience analysis (Figure 2.2, Anderson et al. 2022). Fish studies have found similar faunas in adjacent freshwater ecoregions, and less similar fauna in those separated by latitude or by high elevation mountain chains (Oswood et al. 2000). Based on fish fauna similarities, Oswood (2000) identified several distinct regions which parallel the ecoregions roughly as:

- Alaska-Yukon Tundra (the most dissimilar fish fauna)
- Yukon Basin (Yukon Plateau and Interior Alaskan Taiga)
- Beringian Tundra
- Coastal Southwest (Bristol Bay, Cook Inlet, Alaska Range)
- Southern Maritime (Gulf of Alaska Mountains, Southeast Alaska Forest)

Fishes of the Beringian refuge (local survivors of Pleistocene glaciation) dominate northern regions, with increasing representation southward by fishes derived from the Pacific Coast.

**Figure 2-2. Terrestrial ecoregions of Alaska.**



# Hydrography

To assess streams, rivers, and waterbodies in Alaska, we used available hydrology products and determined their applicability for different components of this resilience analysis. The sources and primary uses in our resilience assessment are described below.

We used the MERIT Hydro raster datasets (Yamazake et al. 2019) to delineate river and stream linework for the Functionally Connected Networks and watersheds for Alaska and the parts of Canada draining into Alaska. The MERIT data were derived from 3 arc-seconds (approx. 90-m) SRTM3 digital elevation data and used a new method of hydrological conditioning and flow delineation with improvements in accuracy of derived river lines and other topographic features. We were unable to use the USGS (2023) National Hydrography Dataset Best Resolution (NHD) - Alaska 1:24,000 because it currently does not have the attributes or topology to support network analysis and accumulation of upstream watershed characteristics, and it did not support integration with Canadian drainages.

For stream, river, and lake diversity, we used RiverAtlas_v10 (Linke et al. 2019). and LakeATLAS_v10.gdb (Lehner et al. 2022) which are based on the hydrography from HydroSHEDS (Ouellet et al. 2019) which derived stream reaches with a drainage area greater than half a square kilometer from a 15 arc-seconds or approximately a 450-m resolution. These datasets provided a large database of attributes for every stream and lake.

.

## Stream and River Size

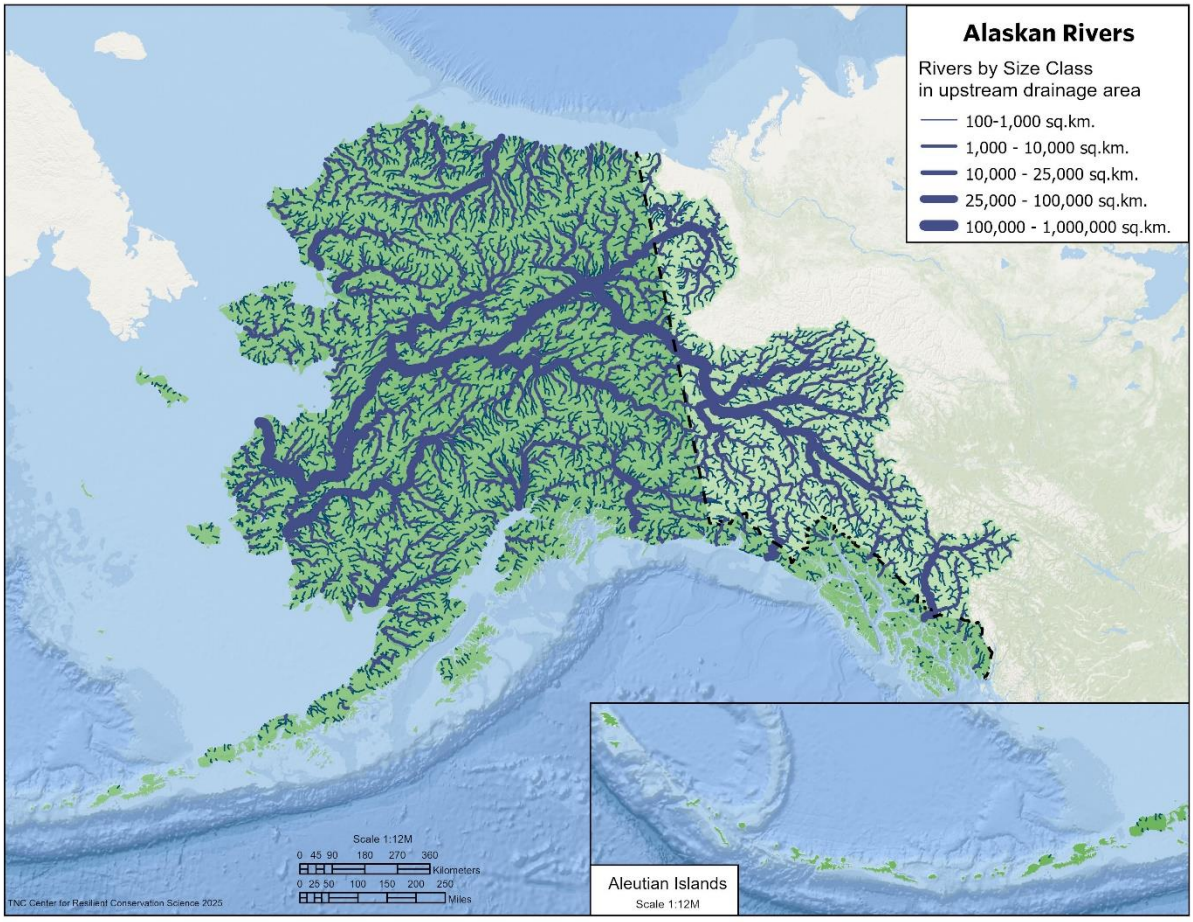
Stream size is indicative of major ecosystem changes along the stream-river continuum, such as transitions in the state and source of energy and ecosystem metabolism (Vannote et al. 1980). Following methods used in our CONUS analysis, we defined stream size based on total upstream drainage area, which is the most stable and geomorphologically comparable measure of size across the country. Size class breaks were based on the National River Fish Habitat Condition Assessment (Wang et al. 2011), which was designed to provide a coarse-level understanding of the diversity of river sizes at a national scale. We made two modifications to the Wang et al. (2011) classification by adding two more size classes for very large rivers (Table 2-1).

Rivers (drainage area over 100 $km^2$) were combined with a dataset of barriers on rivers to create Functionally Connected Networks (FCNs) described later in the Functionally Connected Networks section. Headwater and creek streams (drainage area less than or equal to 100 $km^2$) were assessed separately for fragmentation.

**Table 2-1. River reach size classes.**

| Size Class Number | Size Class Name | Catchment Area ($km^2$) | Category |
|---|---|---|---|
| 1.1 | Headwater Streams | 2 <= 10 | Stream |
| 1.2 | Creek Streams | 10 <= 100 | Stream |
| 2.0 | Small Rivers | 100 <= 1000 | River |
| 3.0 | Medium Rivers | 1000 ≤ 10,000 | River |
| 4.0 | Mainstem Rivers | 10,000 ≤ 25,000 | River |
| 5.0 | Large Rivers | 25,000 ≤ 100,000 | River |
| 6.0 | Great Rivers | 100,000 ≤ 1,000,000 | River |
| 7.0 | Mega Rivers | > 1,000,000 | River |

**Figure 2-3. Rivers by size class.** Alaska contains some of the largest rivers in the U.S.



# Dams and Assessed Road-Related Barriers

A central intent of this study was to estimate the effect of dams and impassable road culverts on species movement by evaluating the location and configuration of barriers on the hydrology network. To do this, we needed spatially accurate data on barriers in Alaska. As our initial step, we compiled barrier information from the following three sources:

**Southern Aquatic Resource Partnership (SARP) Alaska Barriers.** (Draft compilation as of 11_01_2024, 6789 barriers). This dataset had been compiled from multiple sources, data fields crosswalked into a set of consistent fields, and reviewed to remove duplicate points by SARP. It includes 142 dams and 6,647 assessed road-related barriers from 12 sources:

| **Sources** | **Count** |
|---|---|
| Alaska DFG | 2721 |
| American Rivers Dam Removal Database | 6 |
| BIL FY2022 USFWS Proposed Projects | 1 |
| FIS Projects 2023 | 3 |
| NID June 2024 | 2 |
| NID March19 2023 | 103 |
| OpenStreetMap (https://opendatacommons.org/licenses/odbl/) | 17 |
| Tongass National Forest | 2791 |
| USFS Activity Database 2023 | 11 |
| USFS National Activity Database 2023 | 1123 |
| USFS National Surveys database Sep012023 | 6 |
| USFWS FIS 2023 Export | 5 |
| **Total** | **6789** |

Dams in Canada (14) were obtained from two global dam databases. Sources were as follows:

**Global Dam Watch (**CDW**)** Version 1.0: (6 dams) Lehner et al. 2024
**Global Dam Tracker** (GDAT) Version 1.3: (8 dams) Zhang and Vincent 2023

## Passability

Not all dams and road crossings are a complete barrier to aquatic organism passage. Examples of dams that may allow for the movement of some species under certain conditions include dams with fish passage structures, navigation locks, and very small dams that are submerged at high flows. Culverts can also be assessed for passability via field visits and related measurements.

The SARP database provided fields with information on passability, barrier severity, removal date, and fish passage facility which was used to code the barriers into three key passability classes: “0” = complete barrier, “0.5” = partially passable, and “1” = no barrier. We assigned a “0” (n = 2,399) for those barriers coded as complete barriers and for dams with no

information, including all 14 in Canada. We assigned "0.5" (n = 1,011) to those barriers coded as partially passable or with fish passage structure/ladder. We assigned "1" (n = 3,393) for those that were coded as removed or "no barrier" from their assessment. These passability values were used to calculate the cumulative discounted network length described in Chapter 3.

## Results of Barrier Review

We compiled these barriers into a single dataset and used spatial queries and visual inspection of all barriers less than 300 meters from a mapped river (size 2 or larger, n = 468) to determine whether the barrier was across the river or only on a nearby stream (drainage area less than or equal to 100 $km^2$). Dams across rivers were important to distinguish as they were used to create riverine Functionally Connected Networks, while the others were only used in the headwater stream fragmentation metrics. This review revealed that most barriers near rivers were on nearby streams or off channel, not across rivers.

Ultimately, we found only 29 barriers across rivers, while the rest were on streams or off channel. We used this set of 29 river barriers to define the Functionally Connected Networks described below. These river barriers were "snapped" to the river arcs from the MERIT derived hydrology (Figure 2-4).

For the headwater fragmentation analysis, we used all dams on streams and those assessed culverts that were classified as complete barriers. We did not include partially passable culverts in our headwater and creek fragmentation analysis. These stream barriers were snapped to the largest flow accumulation 90-m grid cell within 180 meters of the source position of the point.

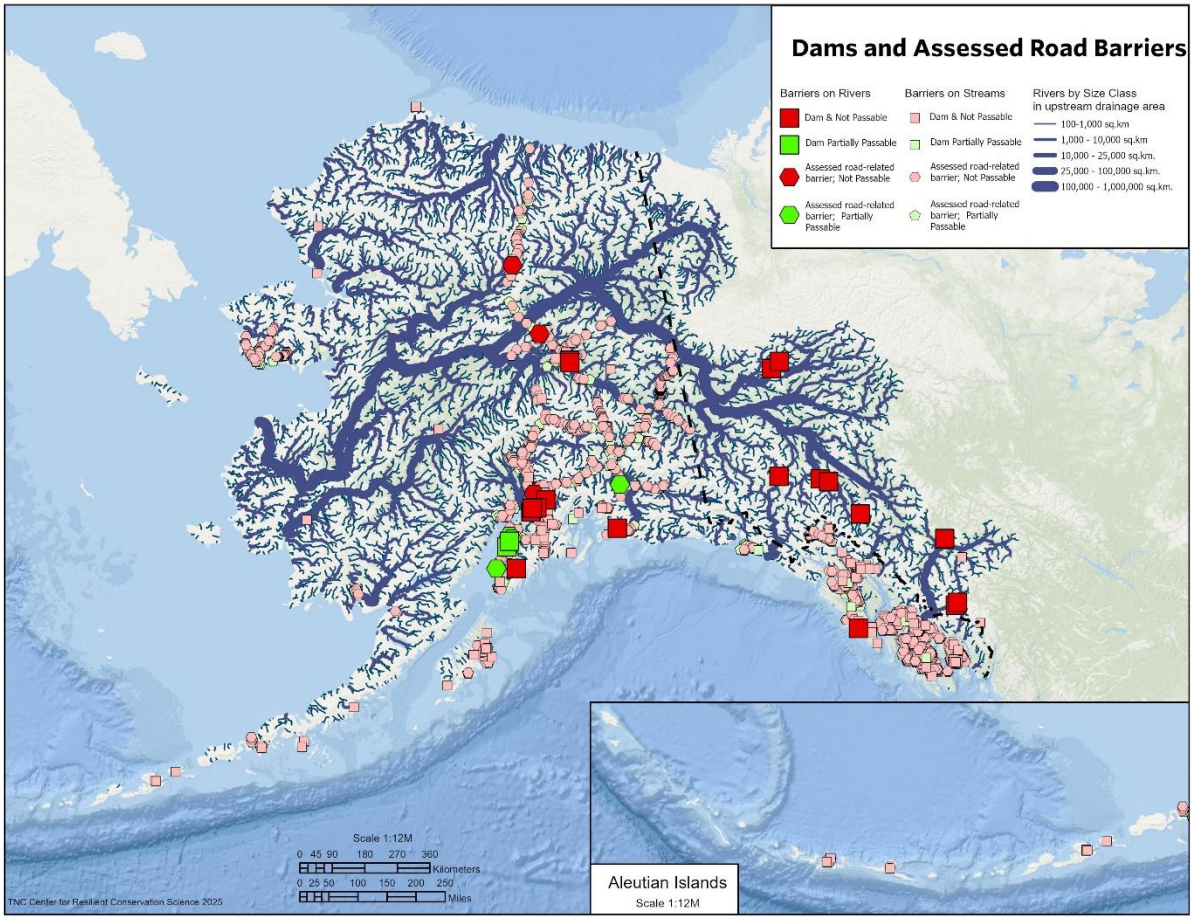
**Figure 2-4. Conceptual illustration of snapping a dam to the river network.**

The final set of partial or complete barriers are described by their type and passability in Table 2-2 and shown in Figure 2-5.

**Table 2-2. Summary of barriers used in Alaska's freshwater resilience analysis.**

| Barrier | River: Across river | Stream: Across stream or channel | Grand Total |
|---|---|---|---|
| **Assessed road-related barrier** | **8** | **3,259** | **3,267** |
| Complete | 3 | 2,263 | 2,266 |
| Partial | 5 | 996 | 1,001 |
| **Dam** | **21** | **122** | **143** |
| Complete | 19 | 114 | 133 |
| Partial | 2 | 8 | 10 |
| **Grand Total** | **29** | **3,381** | **3,410** |

**Figure 2-5. Results of barrier review.** The map shows the location of the 29 partial or complete river dams and the 3,381 headwater stream barriers.



# Analysis Units

The resilience of freshwater ecosystems plays out at multiple spatial scales. To account for this, we used two primary units of analysis:

1) Functionally Connected Networks (FCNs) delineated using the MERIT DEM (Yamazake et al. 2019) and river hydrography (>100 sq.km. upstream drainage area)
2) HUC-12 watersheds derived from the NHD (USGS 2023)

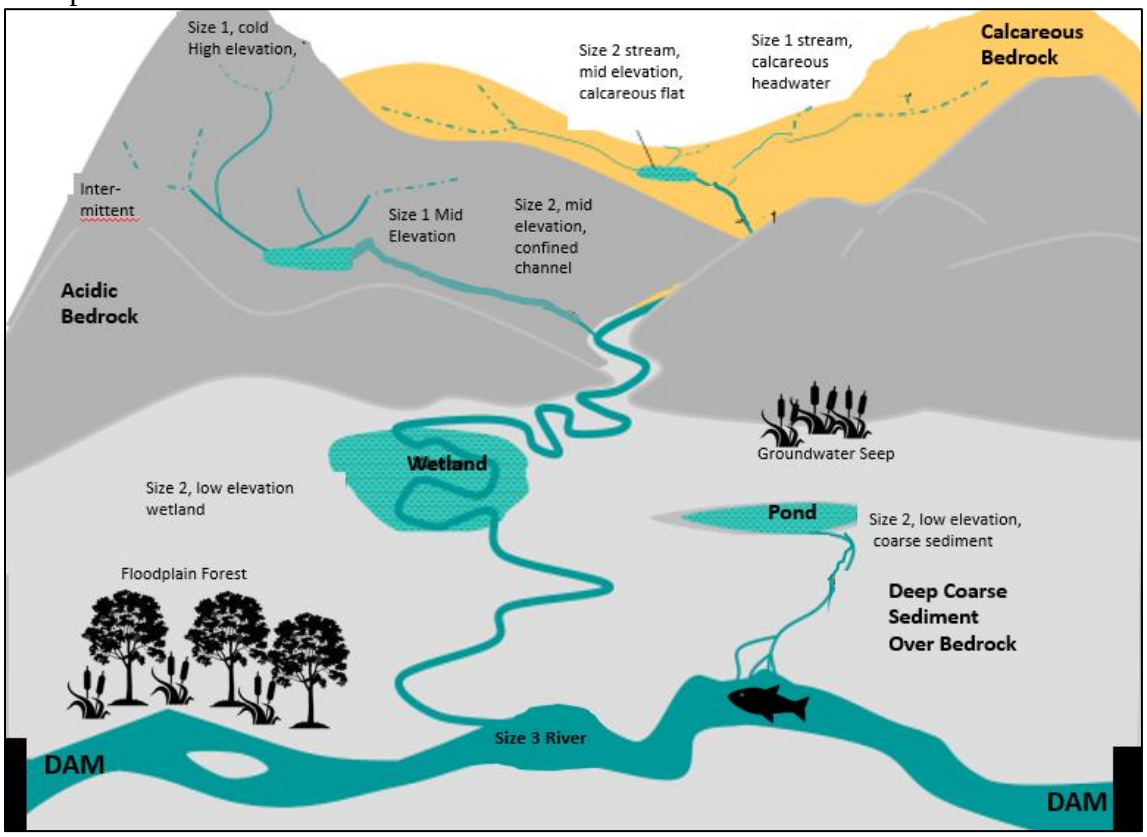
Final resilience scores were assigned to polygons that were the result of the intersection of the HUC-12 and FCN units. Most HUC-12 watersheds nested perfectly within an FCN (86%), but some (14%) were split by an FCN boundary. The split HUCs were primarily along the coast where the land area of the HUC draining to a riverine FCN before emptying into the coast was separated from the land draining only into small streams before emptying into the coast. These HUCs were split by the FCN watersheds if the FCN covered less than 95% of the HUC.

The combined HUC-12-FCN units, henceforth referred to simply as HUC-12s, allowed metrics to be calculated at the appropriate scale and integrated together into the master HUC-FCN polygon dataset. For example, HUC-12 values for connectivity were derived primarily from the size of the FCN in which they occurred, whereas their condition values were derived primarily from HUC-12 watersheds.

## Functionally Connected Networks

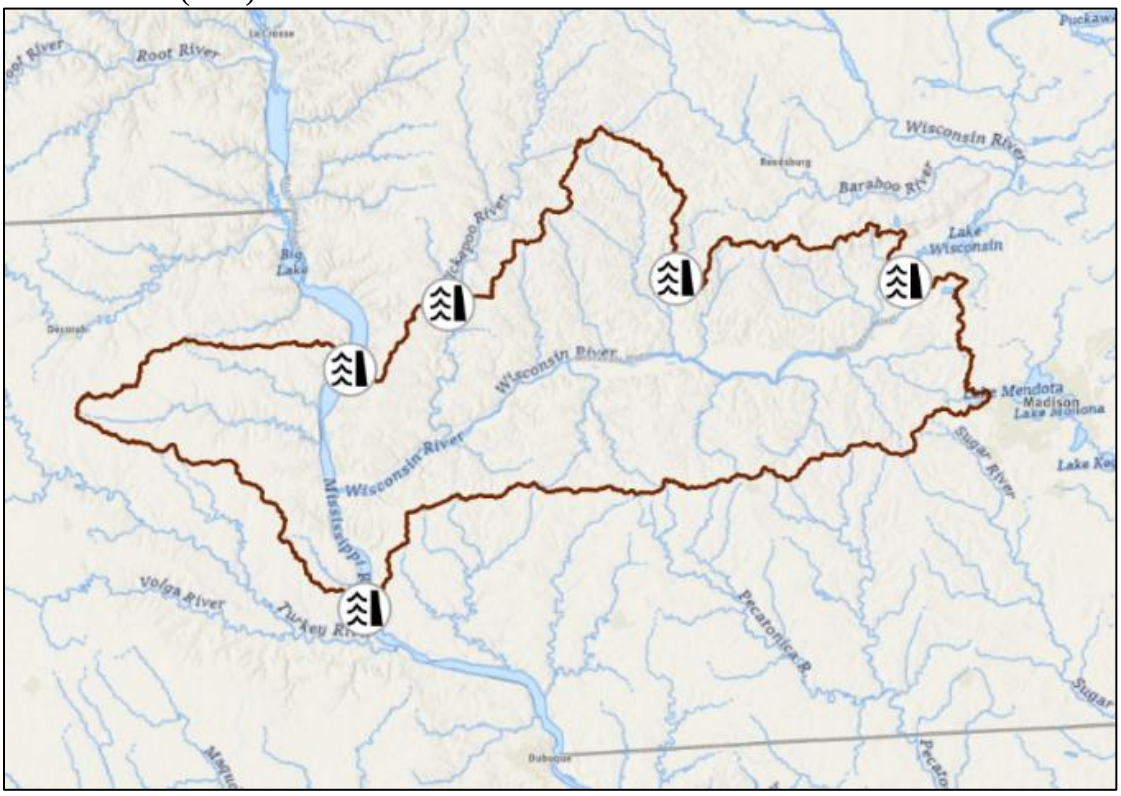
A Functionally Connected Network (FCN) was defined as the amount of locally connected freshwater habitat available for the movement and life history needs of aquatic species. Spatially, we defined an FCN as the set of connected rivers, streams, and headwaters bounded on all sides by river dams, by the upper extent of headwaters, or by the confluence with an ocean. A free-flowing river in FCN terminology is bounded only by its headwaters and mouth, whereas other dam-bounded FCNs can be restricted on all sides by dams or by a combination of dams and headwaters, or all three (Figure 2-6).

**Figure 2-6. A Functionally Connected Network (FCN).** This FCN is bounded by two dams on the river portion and by the headwaters of the two tributaries. The network includes a diversity of bedrocks, slopes, stream temperatures, waterbodies, wetlands, seeps, and floodplain forest.




We created FCNs by intersecting river dams with the project hydrography. The land area draining to the connected set of streams and rivers of each FCN was delineated using the flow direction grid to define the watershed of the FCN. We characterized each FCN by its watershed area (Figure 2-7) rather than the length of its rivers because we found the FCN drainage area to be more closely correlated with the total length of all streams in the network (including headwaters and creeks) and the area accounts for variability in the mapping of the smallest headwater stream lengths.

**Figure 2-7. Example FCN watershed.** The map depicts a single FCN watershed based on dam locations (icon) and local watershed area.




## HUC-12 Watersheds

A Hydrologic Unit (HU) watershed represents the area of the landscape that drains to a portion of a stream network (Figure 2-8). The United States is divided and sub-divided into successively smaller hydrologic units which are nested within each other, from the largest geographic area (HUC-2 "region") to the smallest geographic area (HUC-12 subwatershed). Each hydrologic unit is identified by a unique hydrologic unit code (HUC), a numeric code that corresponds to the level of classification in the hydrologic unit system (Seaber et al. 1987). Figure 2-9 shows how the HUC-12s and reach catchments might nest within the USGS hydrology hierarchy.

**Figure 2-8. Hydrologic Unit Codes (HUCs).** The relative scale of Hydrologic Unit Codes from HUC-2 to HUC-12. Graphic from USGS (public domain)

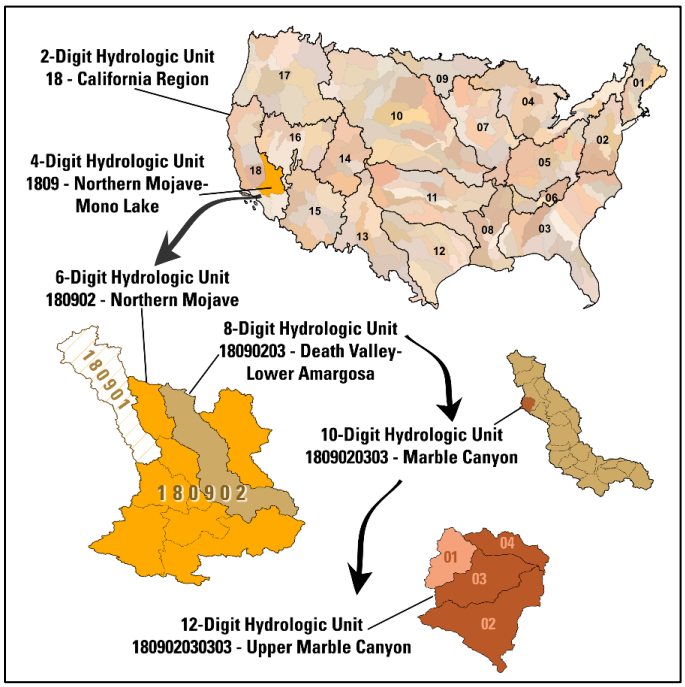
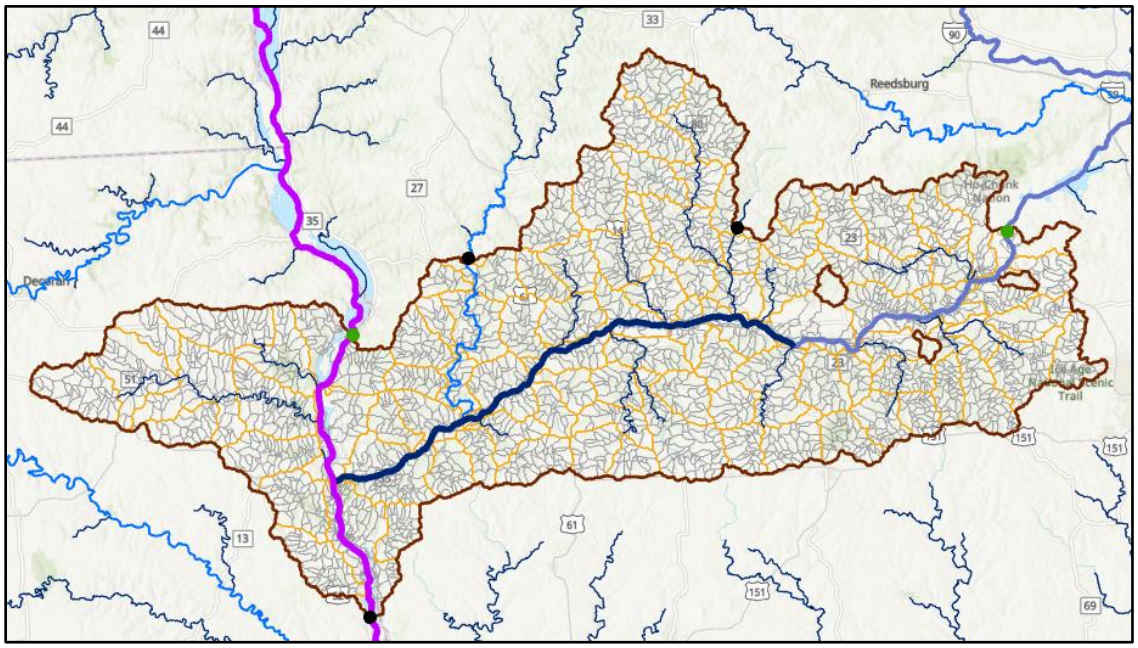



**Figure 2-9. Example of FCN divided by HUC-12s.** This map shows the analysis units of a single FCN. The FCN (brown) is created by five dams, three are full barriers (black) and two are partially passable (green). River line color (blue or purple) and thickness indicate river size class. The HUC-12 boundaries are shown in dark yellow and stream reach catchments in light gray. This FCN contains 93 HUC-12s and 3,730 reach catchments.



## Scoring of the FCN and HUC-12 Units

Throughout this analysis, we scored the FCN and HUC-12 units based on the component datasets and often combined scores into an index. Statistical analyses and data management were performed using R Statistical Software (R Core Team 2024). We transformed all scores to standard normal units (z-scores). A z-score describes the number of standard deviations a value is from the mean of a distribution. Thus, a z-score of "0" equals the mean, a value of "1" is one standard deviation above the mean, and a value of "-1" is one standard deviation below the mean. Z-scores allowed us to combine variables with unequal means and variances and different distribution patterns while retaining equal influence. We capped the z-scores to range from -3 to 3 to avoid giving outliers undue influence, and when necessary, we transformed the input data to approximate a normal distribution before calculating z-scores.

One consequence of this approach is that all scores are relative to the population assessed. This allowed us to identify areas that are relatively more resilient or relatively less resilient (Table 2-3) without knowing exactly how the climate will change.

**Table 2-3. Scoring scale based on z-score standardization.**

| Z-Score Class | Standard Deviation Range |
|---|---|
| Far Above Average | >2 |
| Above Average | 1 to 2 |
| Slightly Above Average | 0.5 to 1 |
| Average | -0.5 to 0.5 |
| Slightly Below Average | -1 to -0.5 |
| Below Average | -2 to -1 |
| Far Below Average | ≤ -2 |

For ease of explanation and communication, we refer to all the watershed units as HUC-12s, but a small proportion (less than 5%) were further split by an FCN making them into smaller units that we kept track of as HUC-FCNs.

CHAPTER

# Mapping Freshwater Resilience

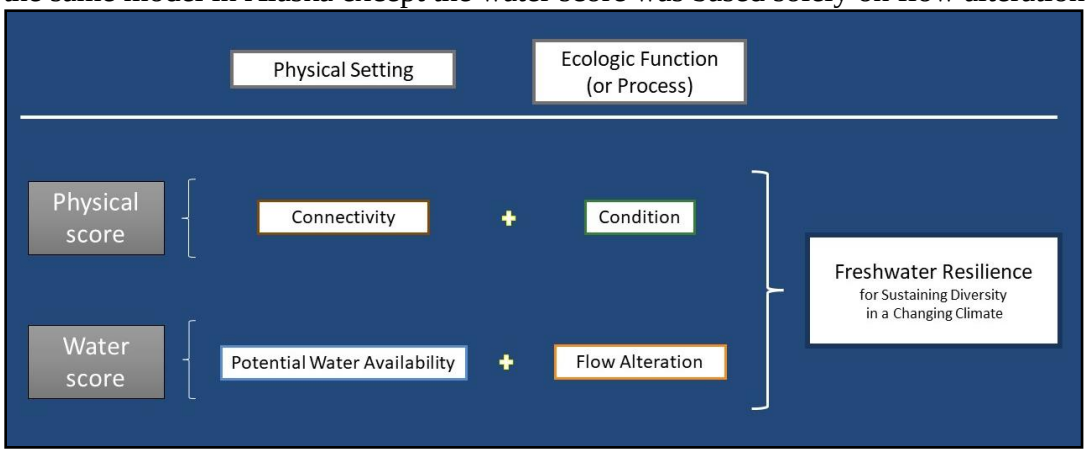
3

In this chapter, we present the model for estimating freshwater resilience. For each component, we explain the metrics calculated and how they were integrated to assess the resilience of each HUC-12.

Our model reflects the hypothesis that the physical setting and its condition, together with water availability and alteration, drive freshwater resilience by providing options and the integrity to maintain ecological function (Paukert et al. 2021). The resilience score estimates the relative capacity of a HUC-12 watershed to maintain species diversity and ecological function as the climate changes. The building blocks of the resilience score are connectivity and condition, which were combined to create a physical score. Flow alteration was used to create a water score. The physical and water scores were then integrated to calculate a freshwater resilience score (Figure 3-1).

These components represent both the physical freshwater stage and the ability of current conditions to provide ecological functions to sustain resilience in the face of climate change. The physical score describes the extent and complexity of the connected freshwater habitat along with its current condition as affected by land use. Both the extent and condition of the network provide organisms with options to move and adapt to changing climatic conditions (Paukert et al. 2021; Pelletier et al. 2020). The water score expresses the importance of the availability of water and the natural flow regime to long-term freshwater resilience (Kaufman et al. 2022; McManamay et al. 2022; Pennock et al. 2022). Each of these main components is calculated from multiple metrics as detailed in the following sections.

**Figure 3-1. Major components of freshwater resilience in the conterminous U.S.** We used the same model in Alaska except the water score was based solely on flow alteration.



# Physical Score

In this section we explain how the physical score was derived. First, we describe the components of connectivity and how they were integrated. Next, we explain how the condition score was calculated from its component metrics and integrated into an index. Finally, we describe how the connectivity score was integrated with the condition score to calculate the physical score.

Our basic model was as follows:

*Physical Score = Connectivity + Condition*

*Connectivity = Functional Connectivity + Diversity*

*Condition = Naturalness + Water Quality*

## Connectivity Score

The connectivity score was comprised of two components, functional connectivity and diversity. The following sections detail how we defined, mapped, and assessed these two elements.

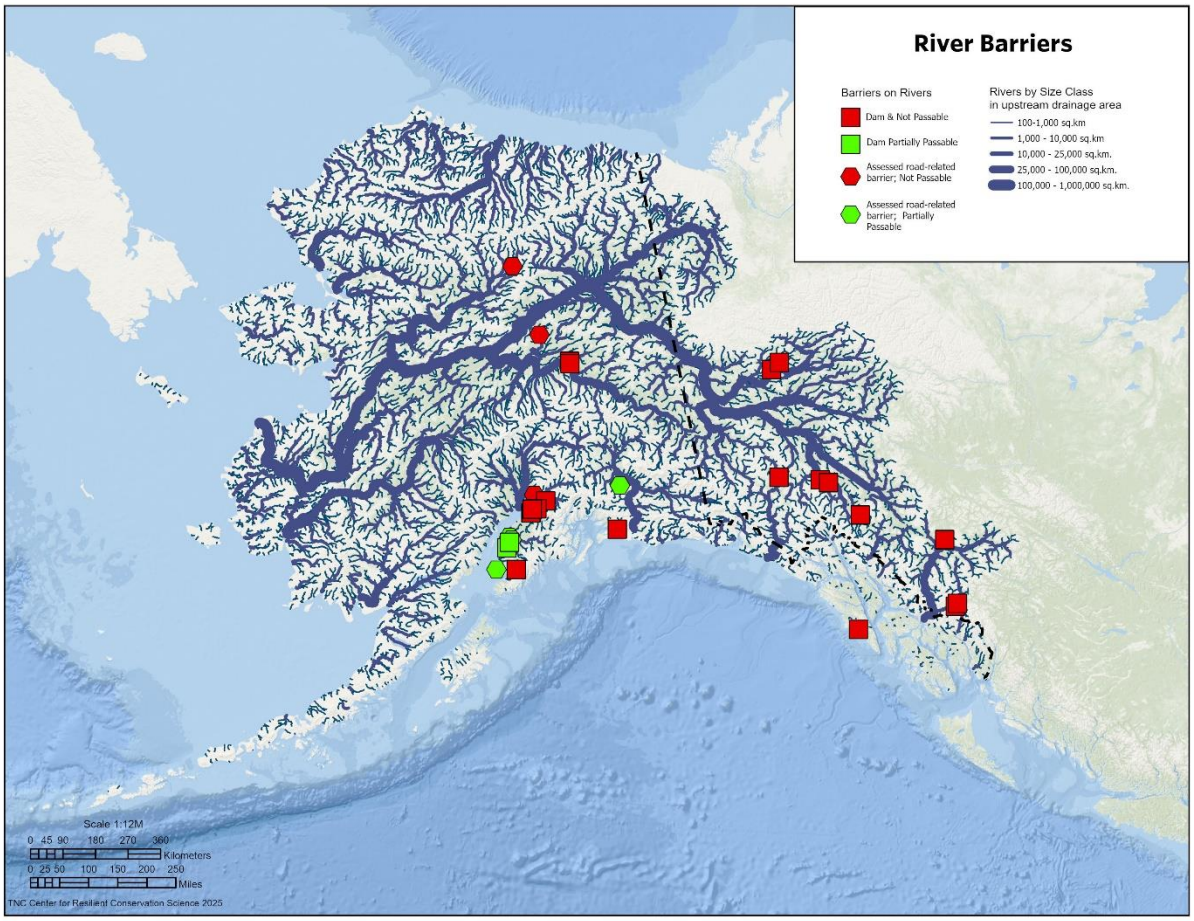
### *Functional Connectivity*

In this analysis, functional connectivity refers to the longitudinal connectivity of a river network accounting for the location of barriers, the passability of those barriers, and the benefits of connection to the ocean. Larger and more complex networks provide greater access to life-stage habitat needs, refugia, and unimpaired riverine processes (Tickner et al. 2020). Connectivity within a network of streams is also essential to support ecosystem processes and recovery from disturbances. It enables water flow, sediment and nutrient regimes to function naturally, allows species to move throughout the network to find feeding and spawning habitat, and in times of stress, enables individuals to relocate in pursuit of more suitable conditions for survival (Pringle 2003). Likewise, disruptions in hydrologic connectivity have had negative ecological impacts on several aquatic faunal groups including migratory fish and native freshwater mussels (Pringle 2003).

Functionally Connected Networks were created using barriers on rivers to fragment the hydrology into unique networks (FCNs), as described in the previous chapter. We report the size of each FCN by delineating a local watershed area draining to each FCN to estimate the amount of connected freshwater habitat and associated land directly draining to each FCN. We used area instead of stream length as a measure of size because tests showed that area better approximated the true size and length of the connected freshwater network when you include all rivers, headwaters, creeks, lakes, ponds, and connected wetlands. The area is also a standard measure, agnostic to differing source stream and river hydrology scales and variation in stream minimum mapping size, which for example allowed direct comparison to the contiguous U.S. FCNs based on 1:100,000 scale hydrography. This approach also allowed us to integrate a suite of characteristics about the land within the whole FCN local watershed draining to a given FCN network.

All else being equal, the larger the connected network, the more likely it is to be resilient because large networks are likely to provide more options for species to move in response to changes in temperature and precipitation and stay within their physiological tolerances (Timpane-Padgham et al. 2017). Connected river networks provide species the ability to disperse to avoid negative impacts of climate change (Comte et al. 2014; Paukert et al. 2021).

**Figure 3-2. River barriers.** This map shows the 29 river barriers used to define FCN boundaries.




## FCN Size Class

The size of the FCNs was skewed towards small values but also contained a few huge outliers. The natural break size distribution of the Alaskan FCNs was very similar to the CONUS distribution which allowed us to apply the same size class rule assignment as used in CONUS (Anderson et al. 2024). We applied the rules and placed Alaskan FCNs into one of 11 national size classes (Table 3-1).

**Table 3-1. FCN national size classes and z-score assignments.**

| Size Class | Name | Area ($km^2$) Thresholds | Z-Score |
|---|---|---|---|
| 1 | Enormous | >100,000 | 3.0 |
| 2 | Huge | >50,000 - 100,000 | 3.0 |
| 3 | Very large | >25,000 - 50,000 | 2.3 |
| 4 | Large | >10,000 - 25,000 | 1.7 |
| 5 | Largish | >5,000 - 10,000 | .99 |
| 6 | Moderate | >2,500 - 5,000 | 0.5 |
| 7 | Smallish | >1,000 - 2,500 | -0.51 |
| 8 | Small | >500 - 1,000 | -1.01 |
| 9 | Very small | >250 - 500 | -1.7 |
| 10 | Tiny | <=250 | -2.3 |
| 11 | Minuscule | < 50 | -3.0 |

Following the CONUS freshwater resilience methods, we then adjusted an FCN's size class to account for the following characteristics that alter the realized size of the network, and thus the availability of habitat to aquatic organisms:

- Dam passability (adjusted size upward for partially passable dams)
- Ocean connectivity (adjusted size upward for ocean connectivity)
- Headwater fragmentation (adjusted size downward for decreased connectivity)

### Accounting for Partially Passable Dams

Our dataset of river dams included seven partially passable dams that allow aquatic organism passage under some conditions. To account for this as we did in the contiguous U.S analysis, we calculated a "cumulative discounted length of streams and rivers" for each FCN bounded by a permeable dam to provide an estimate of the increase in network length. For a given FCN, the cumulative discounted length was calculated by multiplying the permeability of the dam by the length of the FCN on the other side of the dam and continuing in an iterative fashion, multiplying the area of each FCN by the product of all passability scores between it and the given FCN, until a full barrier, coastline, or upper headwater bound was reached (Figure 3-3). Thus, a large FCN immediately adjacent to a given FCN will have more influence on the cumulative discounted value than a large FCN that is accessed via multiple partially passable barriers. The resulting estimated increase is less than if the dam was removed but reflects a proportionally weighted increase in potential access to the networks upstream or downstream. With the integration of the cumulative discounted length, 11 FCNs increased in their length due to the presence of a passable dam upstream or downstream of the FCN.

To estimate the increased *area* of the network after calculating the cumulative discounted length, we used the relationship between the FCN watershed area and the length of FCN rivers plus streams (flowlines > 2 $km^2$ drainage area) by fitting a regression model to the dataset (adj $R^2 = 0.96$, $p < 0.0001$):

$$Area\ (log\ km) = 0.679351558 + 0.973673928\ (FCN\ length\ in\ log\ km)$$

We then evaluated the size class of the predicted watershed area for each network with a cumulative discounted length due to passable dams. In many cases, the small increase in accessible area was not enough to place an FCN into a larger size class, but in some cases the FCN moved up one or two size classes. We capped the increase at two size classes after inspecting the few FCNs that received more than a two-size class increase and to match the methods used in the conterminous U.S. Ultimately, of the 11 FCNs with increased length due to passable dams, six FCNs moved into two larger size classes and one FCN moved into the next larger size class, while four stayed in the same size class as the increased length was not substantial enough to move them into a larger size class (Figure 3-4).

**Figure 3-3. Cumulative-discounted FCN length.** The left network comprises five FCNs defined by four full-barrier dams. The right network shows how the cumulative discounted length was calculated when three of the dams were partially passable.

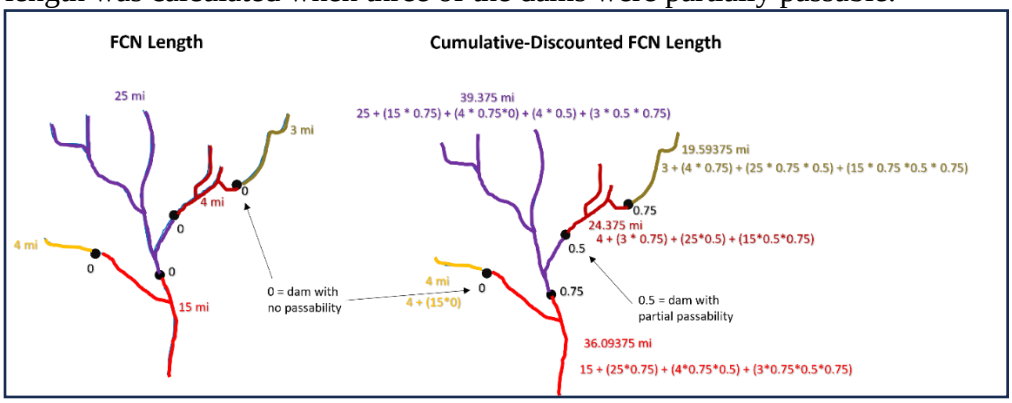
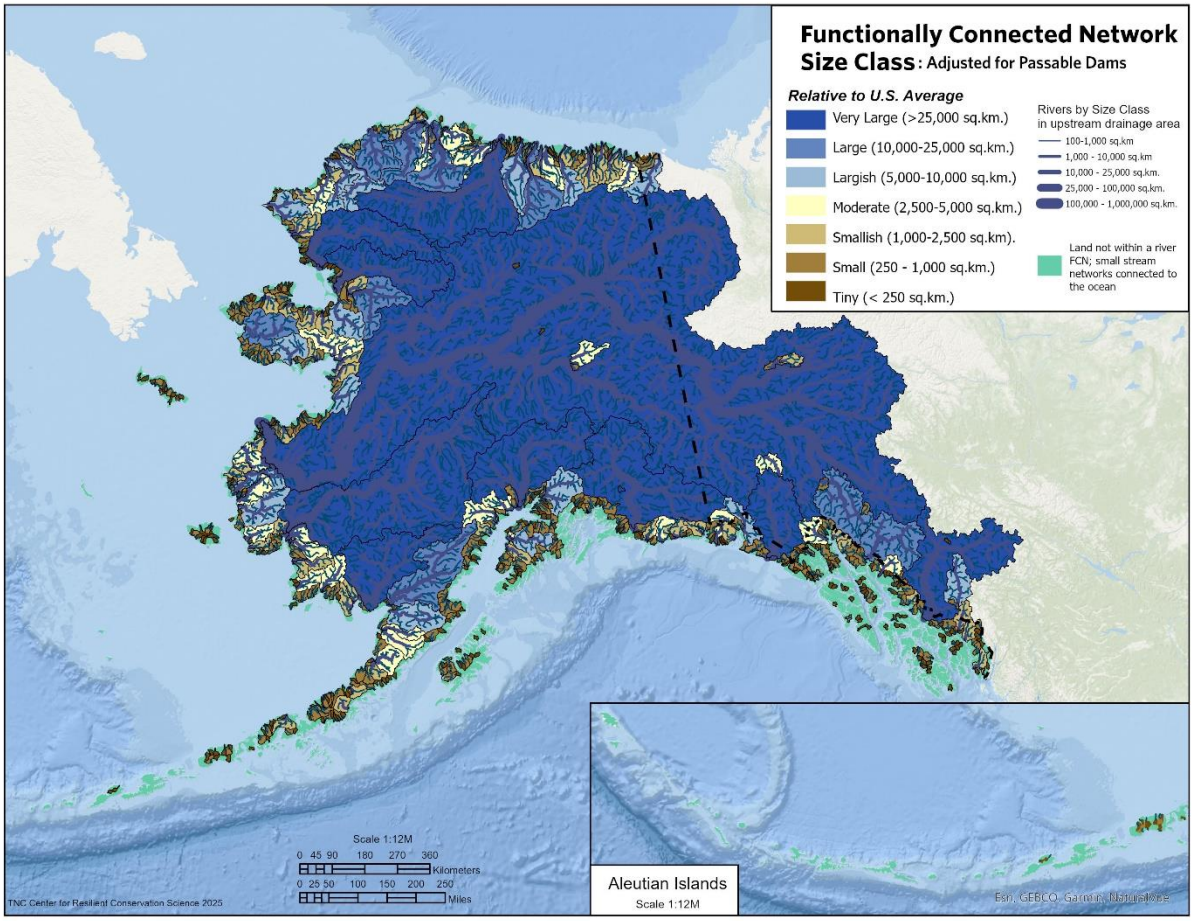


**Figure 3-4. Functionally Connected Network size with adjustment for passable dams.**




## Connectivity to the Ocean

Networks connected to the ocean offer anadromous and catadromous species access to large adjacent ocean and bay habitat. They also offer access to resources in brackish habitats that are used by some freshwater species that can tolerate brackish water and occasionally use these habitats during seasonal movements or dispersals. In Alaska, examples of these kinds of species include the freshwater (normally non-anadromous) Kokanee salmon (Oncorhynchus nerka), Arctic grayling (*Thymallus arcticus*), Whitefish species (e.g., *Coregonus nasus, C. pidschian*), Burbot (*Lota lota*), Lake trout (*Salvelinus namaycush*), Cutthroat Trout (Oncorhynchus clarkii clarkii), and Trout-Perch (*Percopsis omiscomaycus*) (Alaska Fish & Game 2024).

We made further adjustments to the FCN size classes to reflect terminal connections to the ocean and the ability of many aquatic organisms to move through these environments and use resources both in the freshwater and adjacent estuarine and marine environments (Figure 3-5). We increased the size class for ocean-connected FCNs based on the median or mean size of all ocean-connected FCNs following the methods used in the contiguous U.S. We applied the same ocean bump rules given the Alaskan mean and median FCN size of ocean-connected

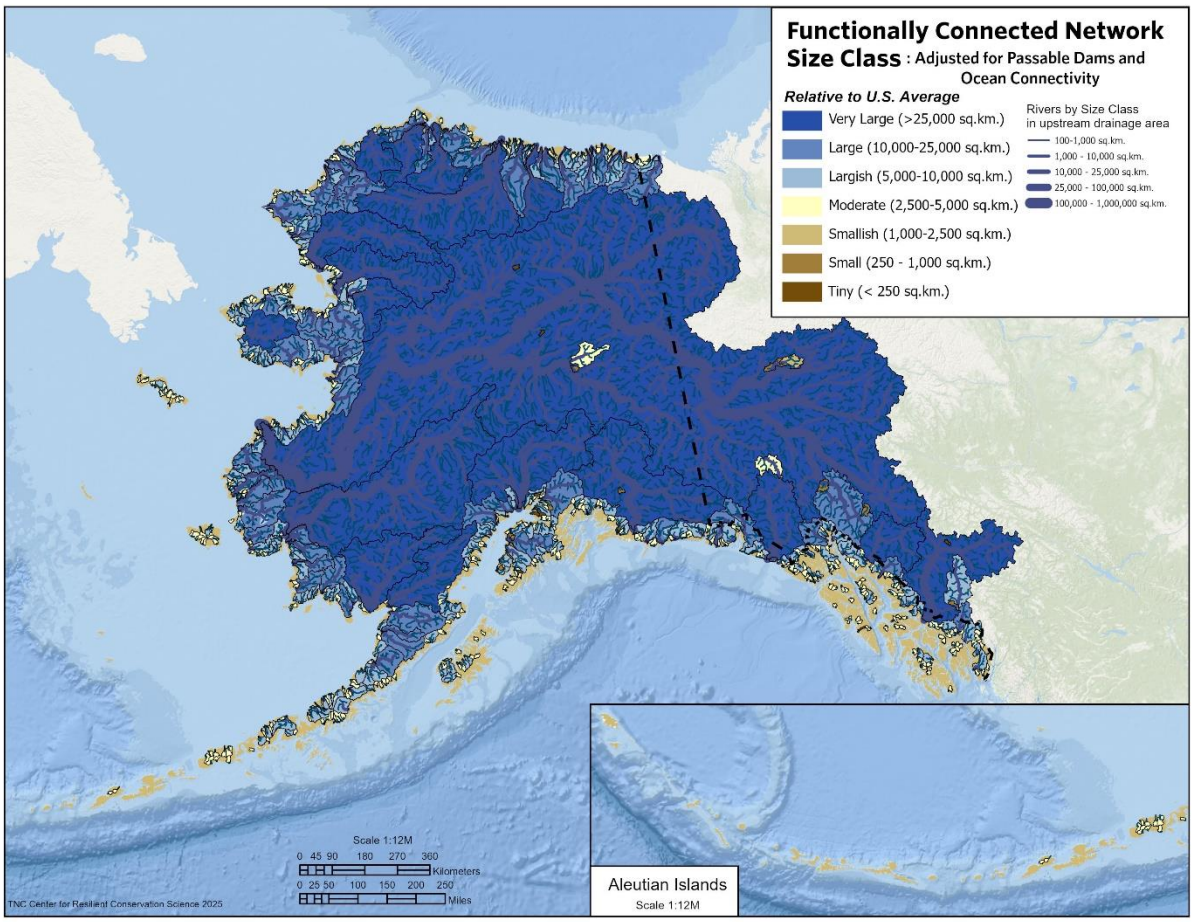
FCNs were very similar to the CONUS mean and median for ocean connected FCNs (mean 2,605, median 254). Applying these rules increased the size class of 582 FCNs.

Rules for ocean-connected FCNs:

1. If already in size class 3 or larger, no change in size class (already in z-score Far Above Average class, z 2.3)
2. If already in size class 4, move to size class 3, which results in going from Above Average to Far Above Average, z 2.3)
3. If greater than the approximate mean US size, 2,000 $km^2$, and less than 10,000 $km^2$, move to size class 4 (Above Average, z 1.7)
4. If greater than the approximate median US size, 300 $km^2$, and less than the mean, 2,000 $km^2$, move to size class 5 (Slightly Above Average, z 0.99)
5. If less than the approximate median size, 300 $km^2$, move to size class 6 (Average class, z 0.5)

A few coastal HUC-12 areas were not part of any FCN because they did not include a mapped river. Rather than exclude these HUC-12s from our analysis, we chose to assign them to size class 7 (Slightly Below Average, z -0.51) based on their downstream connectivity to the ocean, as we did in the conterminous U.S. analysis.

**Figure 3-5. Functionally Connected Network size with adjustment for passable dams and ocean connectivity.**




## Headwater Fragmentation

Headwater connectivity is critical to protecting and maintaining downstream ecological integrity (Alexander et al. 2018). The headwater fragmentation metric expresses how much of the headwater area of a HUC-12, or an FCN, is likely to be connected to its rivers. For this analysis we used the 2,377 complete barriers on headwaters and creeks.

### FCN Headwater Fragmentation

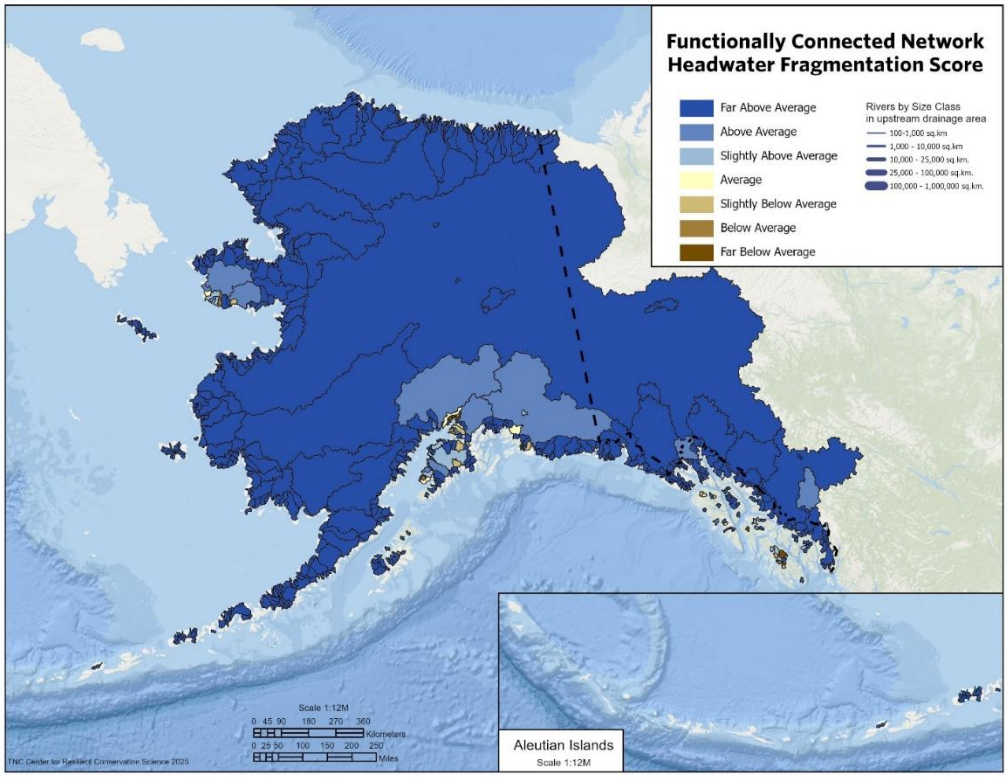
We first delineated the upstream drainage area of each complete barrier on a headwater stream. To calculate an FCN headwater connectivity metric, we divided the largest headwater barrier drainage area in each FCN by the total FCN area. We then assigned FCNs into one of seven categories from very high to no headwater fragmentation. We were unable to use the CONUS-wide natural break classes for FCN headwater fragmentation because the Alaskan values were different from those in the CONUS as Alaska has far fewer dams and less road infrastructure.

We used natural breaks to classify the FCN headwater fragmentation values into seven classes and approximated those classes to z-scores (Table 3-2). We decreased the size score of FCNs with high headwater fragmentation as follows: if FCN headwater connectivity was "Below Average" or "Far Below Average," we lowered the overall FCN size class by one class (n = 12).

**Table 3-2. Assignment of FCN headwater fragmentation values to z-scores.**

| Headwater Connectivity (%) | Natural Break Class | Z-Score Range | Z-Score Class |
|---|---|---|---|
| ≤ 49.45 - 66.50 | 1 | -3 to -2 | Far Below Average |
| > 66.51 - 78.63 | 2 | -2.1 to -1 | Below Average |
| > 78.64 - 87.65 | 3 | -1.1 to -0.5 | Slightly Below Average |
| > 87.66 - 93.60 | 4 | -0.51 to 0.51 | Average |
| > 93.61 - 97.12 | 5 | 0.51 to 1 | Slightly Above Average |
| > 97.13 - 99.05 | 6 | 1.1 to 2 | Above Average |
| 99.06 - 100.00 | 7 | 2.1 to 2 | Far Above Average |

**Figure 3-6. Functionally Connected Network (FCN) headwater fragmentation.** These natural-break classes were translated to z-scores as shown in Table 3-2. FCN watersheds in brown are the most fragmented by the location and/or number of stream barriers while watersheds in blue have few stream barriers or the location of stream barriers has very little impact on overall FCN connectivity.




## HUC-12 Headwater Fragmentation

We also calculated a finer scale headwater connectivity metric by spatially intersecting the HUC-12 watersheds with the previously generated upstream headwater barrier drainage areas. We used the HUC-12 scale of headwater fragmentation later in this chapter to adjust the habitat diversity component of the freshwater resilience physical score.

To calculate the HUC-12 headwater connectivity metric, we divided the largest headwater barrier drainage area in each HUC-12 by the total HUC-12 area (Figure 3-7). We used natural breaks to assign the HUC-12 headwater fragmentation values to seven classes and used those classes to approximate z-scores (Table 3-3, Figure 3-8). Again, we were unable to use the CONUS-wide natural break classes for HUC-12 headwater fragmentation because the Alaskan values were very different from those in the CONUS as Alaska has far fewer dams and less road infrastructure. We also adjusted the size score for the small number of HUC-12s that were not part of any FCN to account for high headwater fragmentation within the HUC-12.

High headwater fragmentation was defined as a HUC-12 that scored “Below Average” or “Far Below Average” or if the size of the remaining network area open to the ocean was less than

50% of the size of the HUC. Size scores were lowered by one class for these 45 HUC units. As these were all ocean-connected coastal units, their size class went from class 7 to class 8.

**Figure 3-7. Example of HUC-12 scale headwater connectivity.** Watersheds in red are the most fragmentated by barriers on streams, while watersheds in green have no stream barriers or the location of stream barriers has a minimal impact on overall connectivity, considering the entire HUC.

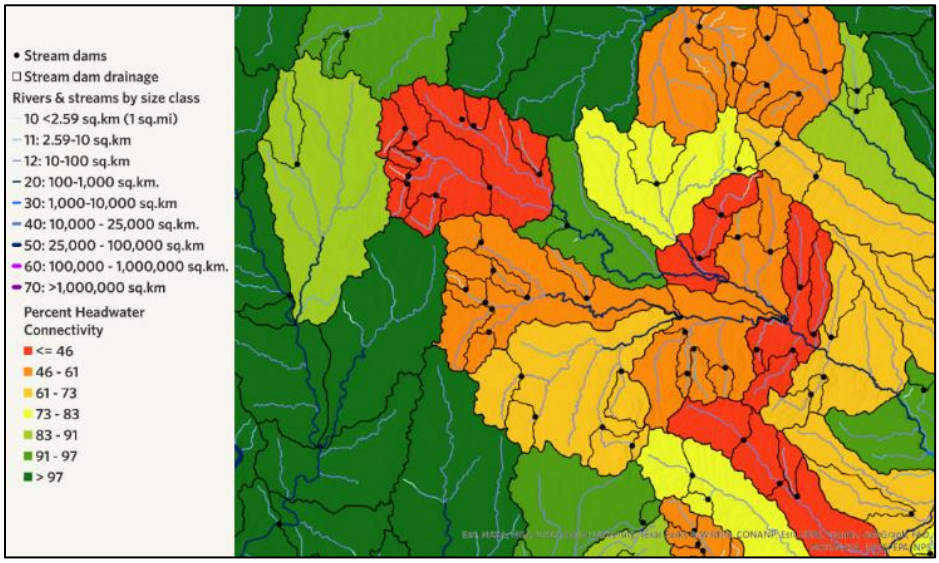
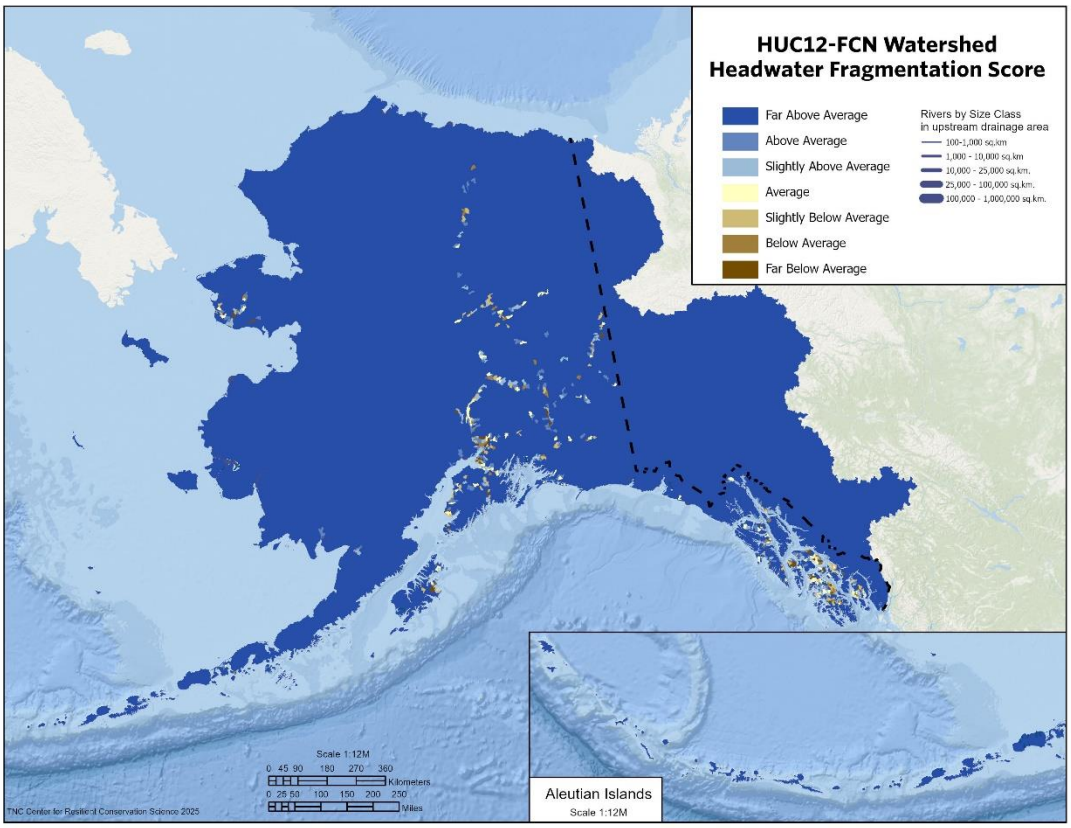



**Table 3-3. Assignment of HUC-12 headwater connectivity values to z-scores.**

| Headwater Connectivity (%) | Natural Break Class | Z-Score Range | Z-Score Class |
|---|---|---|---|
| 26.78 - 52.54 | 1 | -3 to -2 | Far Below Average |
| > 52.55 - 67.07 | 2 | -2 to -1 | Below Average |
| > 67.08 - 79.31 | 3 | -1 to -0.5 | Slightly Below Average |
| > 79.32 - 88.33 | 4 | -0.5 to 0.5 | Average |
| > 88.34 - 94.20 | 5 | 0.5 to 1 | Slightly Above Average |
| > 94.21 - 98.26 | 6 | 1 to 2 | Above Average |
| > 98.27 - 100.00 | 7 | >2 | Far Above Average |

**Figure 3-8. HUC-12 headwater connectivity fragmentation classes.** These natural-break classes were translated to z-scores as shown in Table 3-3. Watersheds in brown are the most fragmented by the location and/or number of stream barriers while watersheds in blue have no stream dams or the location of stream dams has very little impact on headwater connectivity.




## Final Functional Connectivity Size Score

All the foregoing adjustments were used to determine the final functional connectivity size score. Figure 3-9 shows the FCN and HUC-12 units that received a size class adjustment and the reason for the adjustment (i.e., dam passability, ocean connectivity, headwater fragmentation). Figure 3-10 shows the functional connectivity size score for each FCN based on the original size of the riverine network adjusted for passable dams, connectivity to the ocean, and headwater fragmentation.

**Figure 3-9. FCN and HUC-12 units adjusted for functional connectivity by type of adjustment.**

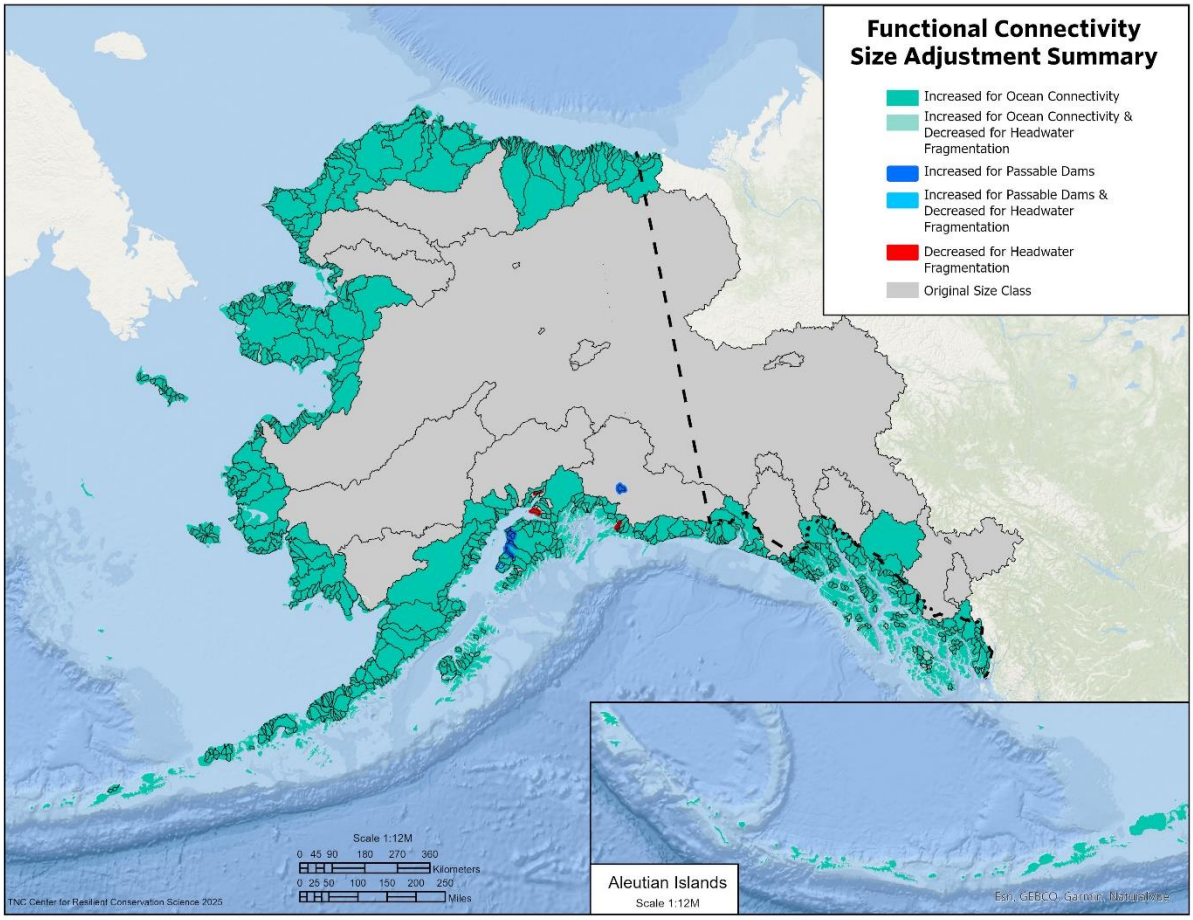
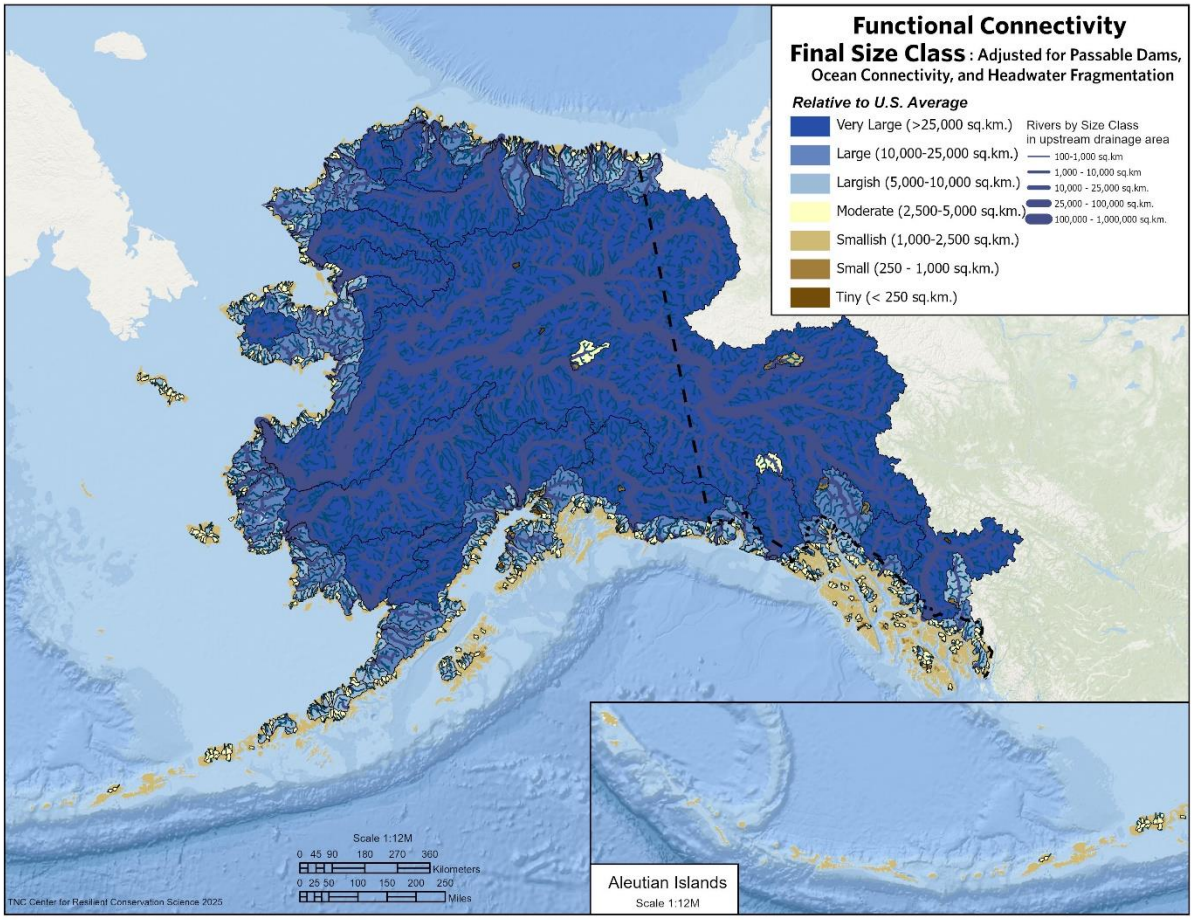


**Figure 3-10. Final Functional Connectivity size class.** This map shows the functional connectivity size score for each FCN based on the original size of the riverine network adjusted for passable dams, connectivity to the ocean, and headwater fragmentation.




## *Diversity*

The diversity score measures the physical habitat variation within the connected networks. Greater connectivity increases the opportunity for dispersal, while more variation in aquatic habitat types offers more options for species to find suitable habitats and resources which increases resilience and metapopulation stability (Pelletier et al. 2020). With climate change, many species are moving northward seeking cooler waters, but a diversity of local temperatures, gradients, size classes, and aquatic habitats also creates options for species to find suitable conditions as conditions change. We calculated a habitat diversity score by tabulating the number of stream and river types, shallow or deep lakes, and presence of tidal aquatic habitats within each HUC-12. The habitat diversity features are described in detail below.

### Stream and River Types

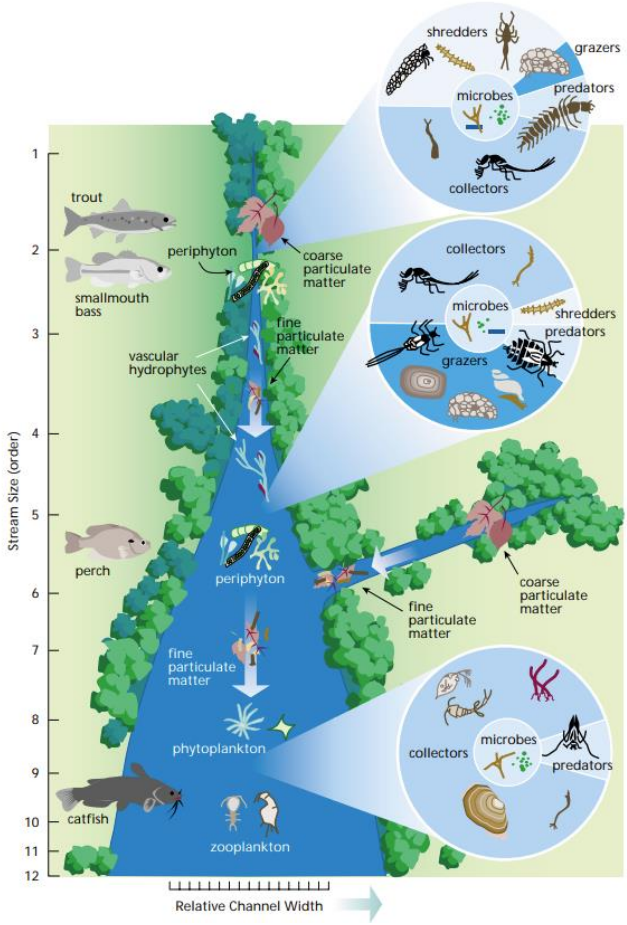
Macrohabitats are the finest scale unit of hierarchical aquatic classification types defined in TNC's freshwater classification approach (Higgins et al. 2005). They define stream reach types or lake types and are based on key abiotic variables known to structure aquatic communities at the reach or lake scale.

For this analysis, we created simplified macrohabitat types to represent variation in major aquatic physical habitats at the stream reach or individual lake scale using variables possible to model in GIS. Stream and river macrohabitat attributes came from RiverAtlas_v10 (Linke et al. 2019) and HydroSHEDS (Ouellet et al. 2019) which contained a large database of attributes for each reach. We extracted size, gradient, and temperature as the key habitat variables to integrate into unique macrohabitat type codes following guidance from Higgins et al. (2005).

## Size

Stream size is indicative of major ecosystem changes along the stream-river continuum, such as transitions in the state and source of energy and ecosystem metabolism. Stream size has been given the highest classification importance in many reach-scale stream classification systems because of its strong effect on determining aquatic biological assemblages at the reach scale (Vannote et al. 1980; Higgins et al. 2005). The well-known "river continuum concept," depicted in Figure 3-11, illustrates how the physical size of a stream relates to major ecosystem changes from small headwater streams dominated by coarse organic matter to autochthonous production by plankton in large river mouths (Vannote et al. 1980).

**Figure 3-11. The River Continuum Concept from Vannote et al. (1980).**




Size classes were based on total upstream drainage area which is the most stable and geomorphologically comparable measure of size. Size class breaks were based on the National River Fish Habitat Condition Assessment (Wang et al. 2011) which was designed to provide a coarse-level understanding of diversity at a national scale (Table 3-4).

**Table 3-4. River reach size classes.**

| Size Class Number | Size Class Name | Catchment Area ($km^2$) |
|---|---|---|
| 11 | Headwaters | ≤ 10 |
| 12 | Creek | <100 |
| 20 | Small Rivers | ≤ 1000 |
| 30 | Medium Rivers | ≤ 10,000 |
| 40 | Mainstem Rivers | ≤ 25,000 |
| 50 | Large Rivers | ≤ 100,000 |
| 60 | Great Rivers | ≤ 1,000,000 |

# Gradient

Stream gradient also highly influences aquatic communities at the reach scale due to its influence on stream bed morphology, flow velocity, sediment transport/deposition, substrate, and grain size (Rosgen 1994). As shown in Figure 3-12, high gradient streams are dominated by step-pools to plane-bed systems with substrates of cobble and boulders, and colluvial sediment transport. Low gradient systems are dominated by riffle-pool systems, with substrates of sand, gravel, and cobble, alluvial storage, and depositional sediment regimes. Very low gradient streams are dominated by ripple-dune streams with very high sinuosity. These rivers have sand, gravel, and finer sediment substrates, alluvial storage and depositional sediment regimes, and slight entrenchment with critical adjacent floodplain systems (Rosgen 1996; Allan 1995).

**Stream gradient was available for each reach catchment in RiverAtlas (Linke et al. 2019) based on elevation from EarthEnv-DEM90 (Robinson et al. 2014). The stream gradient was calculated as the ratio between the elevation drop within the river reach (e.g., the difference between min. and max. elevation along the reach) and the length of the reach. The continuous stream gradient values were grouped into five classes (Table 3-5) following guidance from a national stream classification (McManamay et al. 2019) and as applied in the conterminous U.S. freshwater resilience analysis.**

**Figure 3-12. Illustration of how gradient shapes riverine habitats (FISRWG 1998).**

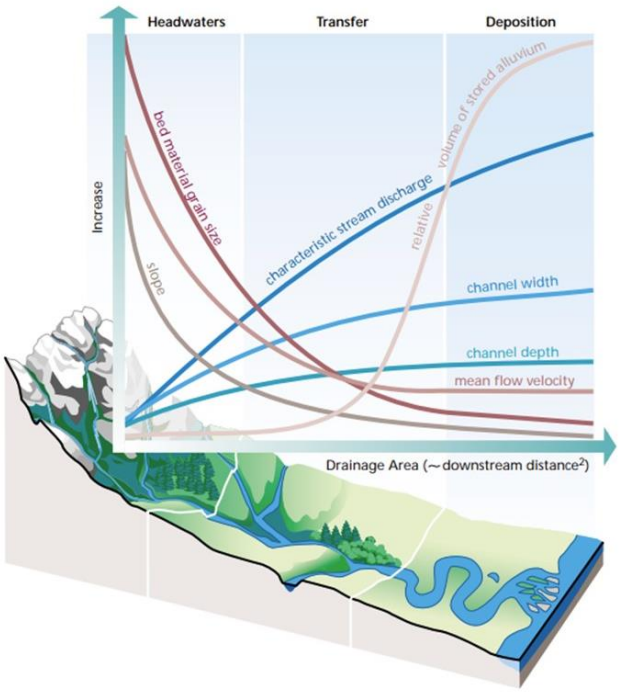


**Table 3-5. Gradient classes.**

| Gradient Class Name | Slope (decimeters/km) |
|---|---|
| Very Low | <10 |
| Low | 11-50 |
| Moderate | 51 - 200 |
| Moderate - High | 201 - 400 |
| High and Steep | >400 |

# Local Temperature

Stream temperature is fundamental to freshwater resilience because it sets the physiological limits of persistence for many organisms and temperature extremes may directly preclude certain taxa from inhabiting a water body. Seasonal changes in water temperature often cue development or migration, and temperature can influence growth rates and fecundity. Ideally, a resilient stream network would span a range of current temperatures offering options for both coldwater and warmwater species and provide connected habitats for species to stay within their thermal preferences in the future (Woodward et al. 2010). Even for cold water fish species, recent research is showing accessible warmer water habitats significantly supports the survival of cold-water fish, such as salmon and trout (Armstrong et al. 2021).

Air temperature data was available for each reach catchment in RiverAtlas from WorldClim v1.4 (Hijmans et al. 2005). The data was based on 30 arc-second monthly air temperature grids, and we used the summary metric of "annual maximum temperature in the reach catchment" to place reaches in one of five classes using natural breaks (Table 3-6).

**Table 3-6. Temperature classes in Celsius and Fahrenheit.**

| Temperature Class | Celsius | Fahrenheit |
|---|---|---|
| 1 | <8 | < 46.4 |
| 2 | 8 - 10 | 50 |
| 3 | 10 - 12 | 53.6 |
| 4 | 12 - 14 | 57.2 |
| 5 | >14 | >57.2 |

# Tidal

Streams and rivers that connect directly to the ocean or to large tidal river estuaries have water flow and levels that fluctuate with the tides, and salinity can range from fresh to brackish to saline. These reaches offer a unique diversity of habitats and resources for anadromous, diadromous, and euryhaline species. We classified each HUC-12 unit as containing tidal habitat based on direct adjacency to the ocean or having a mapped tidal river or tidal wetland habitat from the Alaska Vegetation and Wetland Composite (Alaska Center for Conservation Science, 2022)

# Lakes

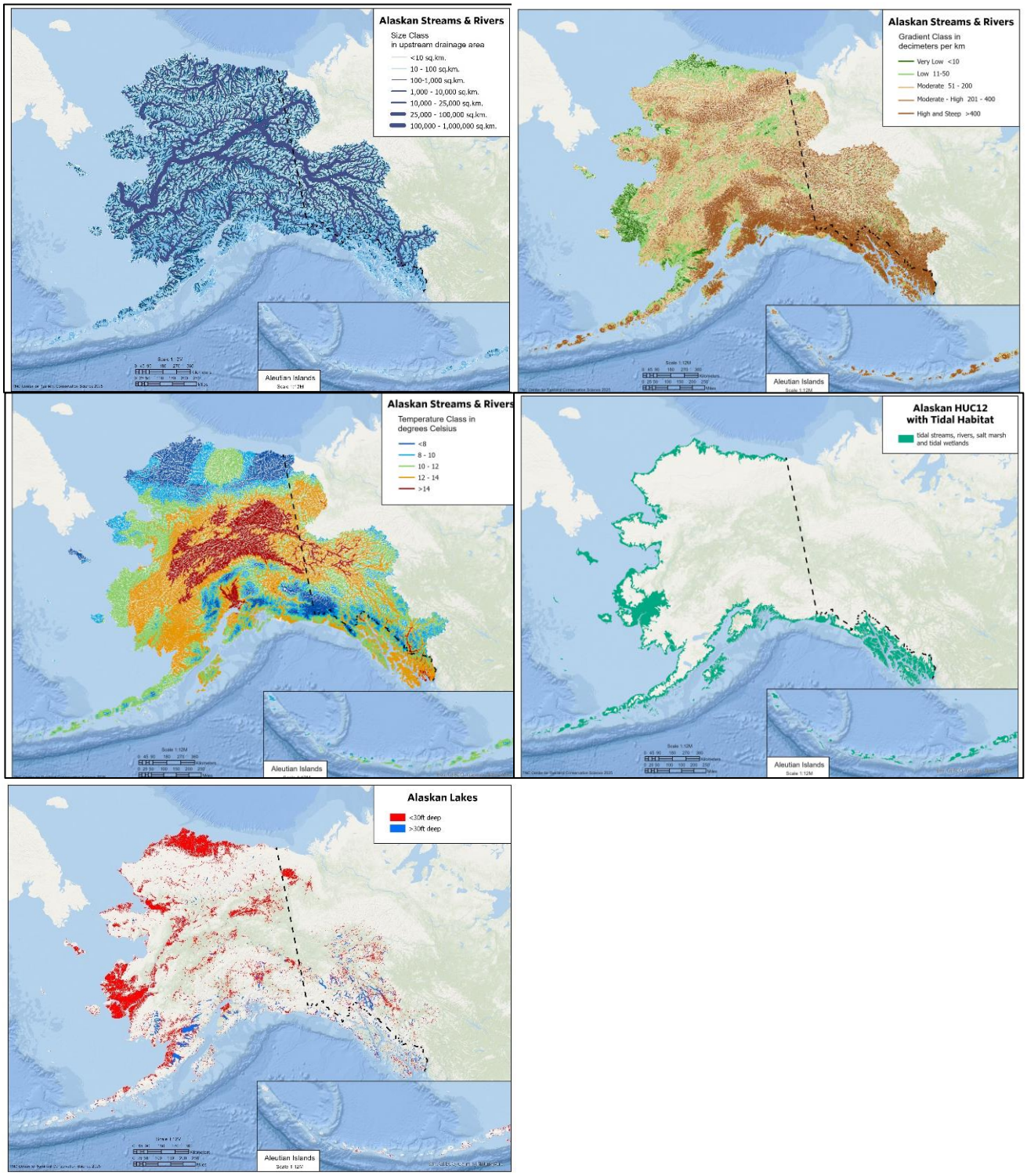
Depth is a critical variable related to summer lake stratification and the presence of deep permanent coldwater. For the diversity analysis, we classified the lakes from LakeAtlas_v10 (Lehner et al. 2022) into two types: 1) deep, > 30 ft., and 2) shallow, < 30 ft.

A summary of the five components and their classes is provided in Table 3-7 and Figure 3-13.

**Table 3-7. Macrohabitat component class summary.**

| Size Class (cumulative drainage area in km$^2$) | Gradient | Temperature | Tidal | Lakes |
|---|---|---|---|---|
| Headwater (2 ≤ 100) | Very low (<0.001) | <8 C | Tidal | Deep |
| Creek (10≤ 100) | Low (0.001 – 0.005) | 8-10 C | | Shallow |
| Small River (>100 & ≤ 1,000) | Moderate (0.005 – 0.02) | 10-12 C | | |
| Medium Rivers (>1,000 & ≤ 10,000) | Moderate-High (0.02 – 0.04) | 12-14 C | | |
| Mainstem Rivers (>10,000 & ≤ 25,000) | High & Steep (>0.04) | >14 C | | |
| Large Rivers (> 25,000 & ≤ 100,000) | | | | |
| Great Rivers (> 100,000) | | | | |

**Figure 3-13. Macrohabitat components.** Clockwise from top: size classes, gradient classes, temperature classes, tidal class, and lake depth classes.



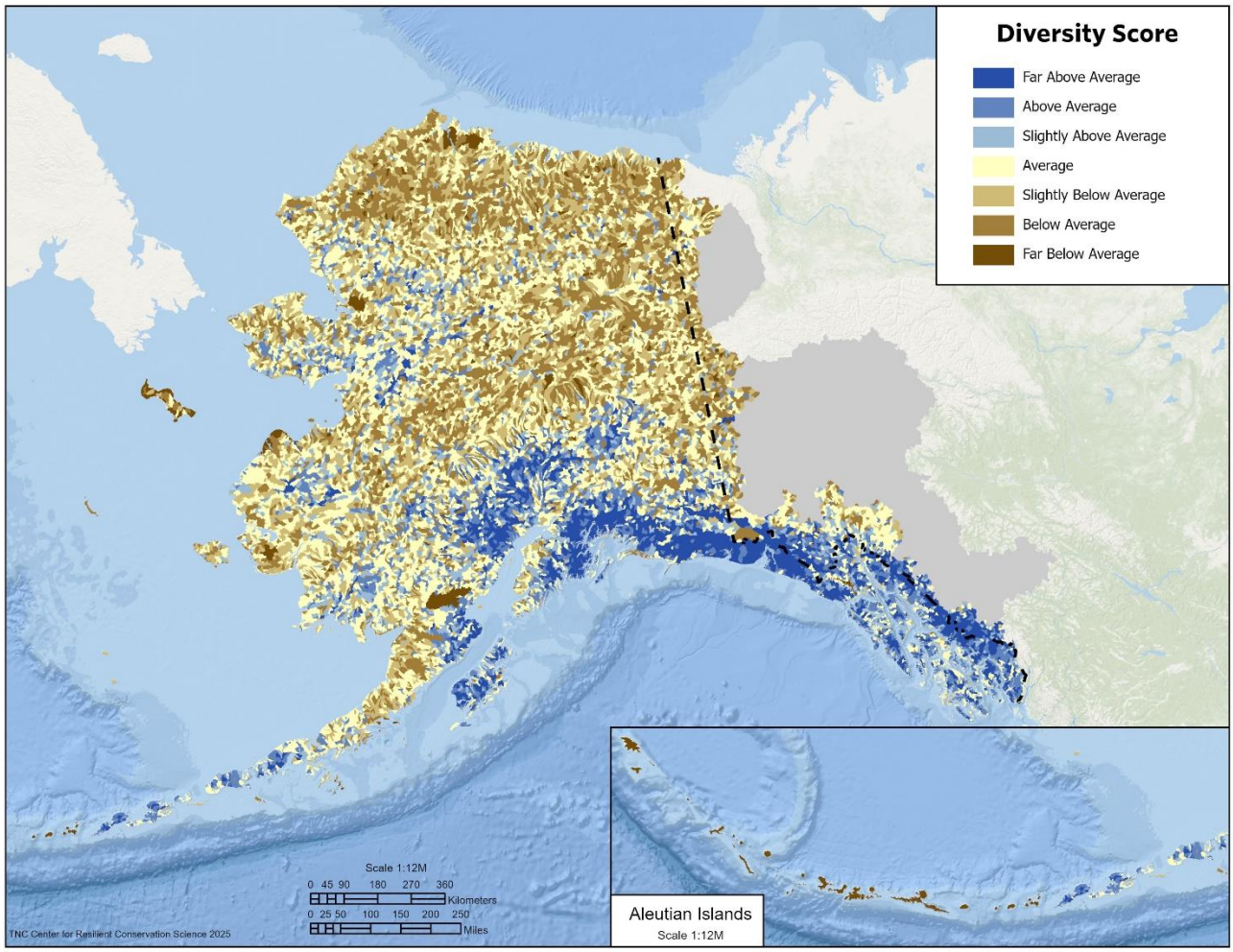
## Calculating Macrohabitat Diversity

The macrohabitat components were combined at the reach scale to code each reach with its size class, temperature class, and gradient class. Each unique combination of these classes was considered a "macrohabitat." All macrohabitat types within a HUC-12 were counted toward a total diversity count of stream and river types present in the HUC-12. The presence of a deep lake or shallow lake or tidal habitat was then added to the total stream-river macrohabitat counts to increase the total by count of aquatic habitats present.

Because the count of macrohabitats was correlated with the size of the HUC-12, we used a Poisson regression to establish a relationship between the size of the HUC-12 and the count of macrohabitats, and then calculated the standardized residuals to identify HUC-12s that had more or less macrohabitat diversity than expected for their size. The standardized residuals were used as the z-score. See details of the statistical models below.

We adjusted the score in HUC-12s that had high headwater fragmentation. Small dams and impassable road crossings on headwaters and creeks make the accessibility of all types of macrohabitats within a HUC-12 more difficult. In HUC-12s with "Average" or worse headwater fragmentation, we adjusted the macrohabitat diversity score by taking the average of the combined macrohabitat diversity z-score and the headwater fragmentation z- score. If the HUC-12 had less headwater fragmentation, we kept the diversity score as it was, based on the assumption that some portion of the macrohabitat types present in the HUC-12 would probably be accessible at some part of the year. We mapped the resultant adjusted diversity score (Figure 3-14).

**Figure 3-14. Diversity score.** This map shows the HUC-12 macrohabitat diversity scores.

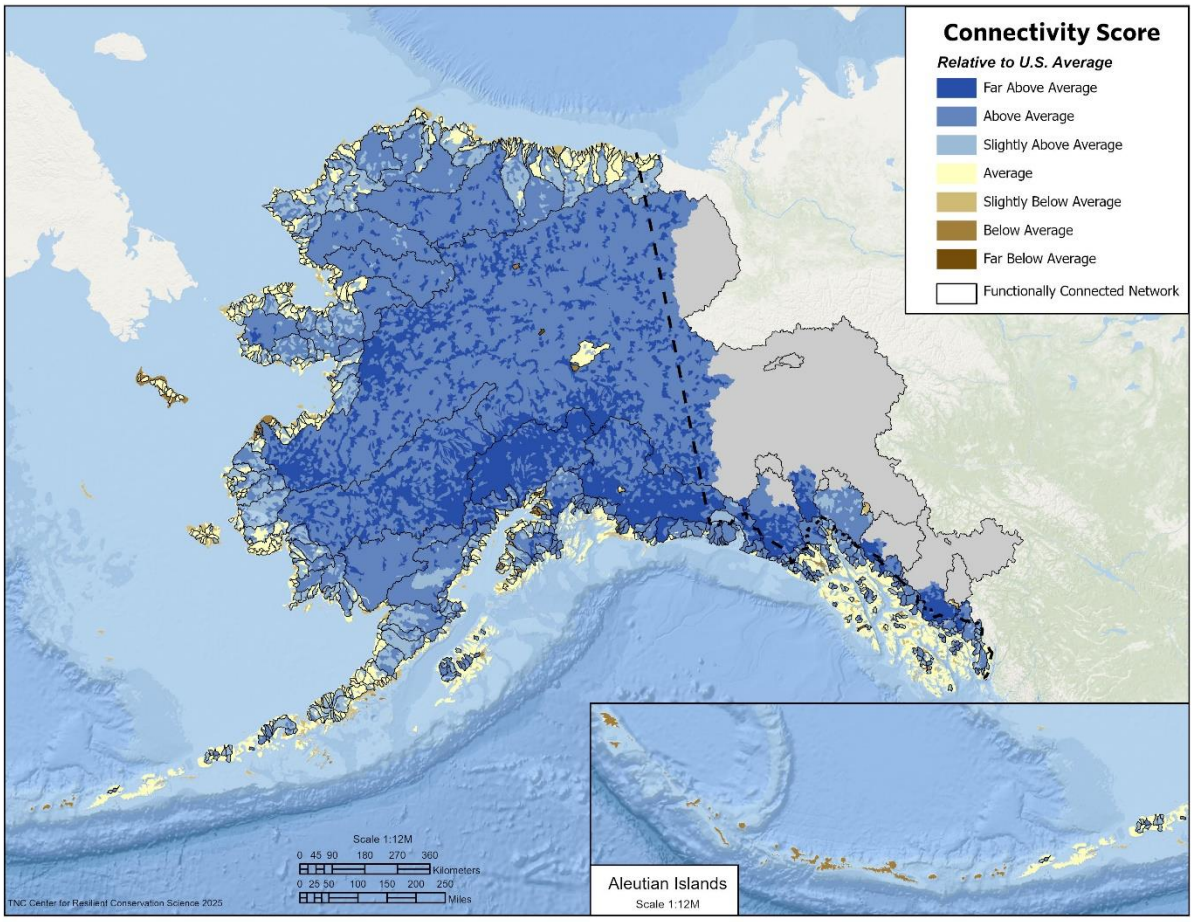



## *Integrated Connectivity Score*

*Connectivity Score = (2*Functional Connectivity + 1*Diversity) / 3*

Our final step was to integrate the functional connectivity size score measured at the FCN scale with the diversity score measured at the HUC-12 scale (Figure 3-15). The aim was to reflect both the whole FCN network size and the more local HUC-12 habitat diversity in a single index for each HUC-12. Given the importance of FCN network size to the availability of habitats, we gave functional connectivity twice the weight as local diversity in our combined index.

**Figure 3-15. Final connectivity score.** In this index, the size of the FCN network was given twice the weight of the local HUC-12 watershed habitat diversity.




# Condition Score

Condition is a measure of current ecological function from landscape influences and accounts for two key ecological attributes of freshwater systems, habitat quality and water quality. Our condition assessment in Alaska was informed by our CONUS freshwater resilience analysis and two recent Alaska watershed assessments (Esselman et al. 2011; Aho et al. 2020).

## *Naturalness*

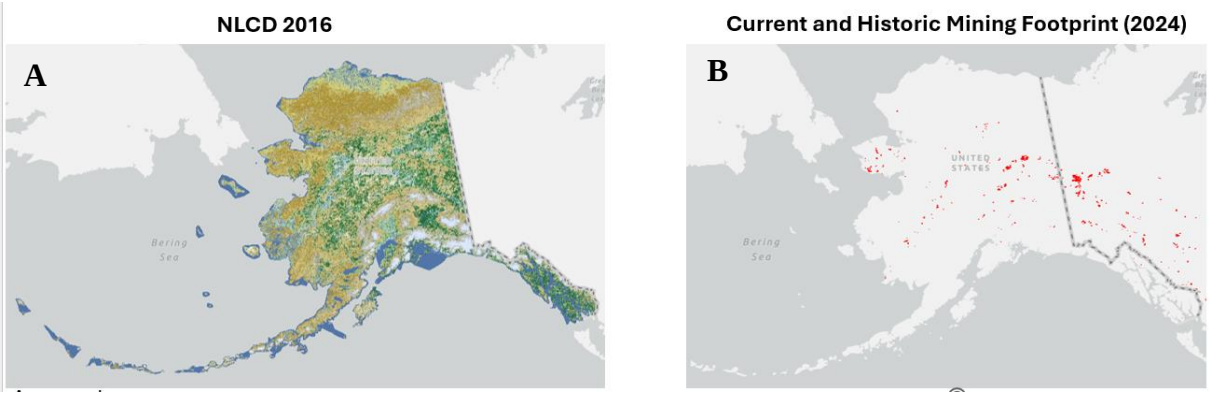
*Naturalness = Floodplain and/or Riparian Naturalness + Watershed Naturalness*

In this section, we assess the naturalness of three essential freshwater features, floodplains, riparian areas, and watersheds. For each feature, we first developed a map of its extent and then overlaid land cover data to quantify the types and amounts of natural, agricultural, and developed land within the extent.

## Landcover

To measure current land use, we combined the most recent National Land Cover Dataset (NLCD 2016) available for Alaska with a recent mining footprint dataset (Geist et al. 2017). The mining footprint dataset was developed by the Alaska Center for Conservation Science (ACCS) at the University of Alaska Anchorage (UAA), in partnership with the Northwest Boreal Landscape Conservation Cooperative (NWB LCC). The dataset depicts historical and current ground disturbance resulting from surface mining across Alaska and Northwest Canada. We merged the mining footprint on top of the land cover as a value of "10" to override the NLCD pixel values underneath.

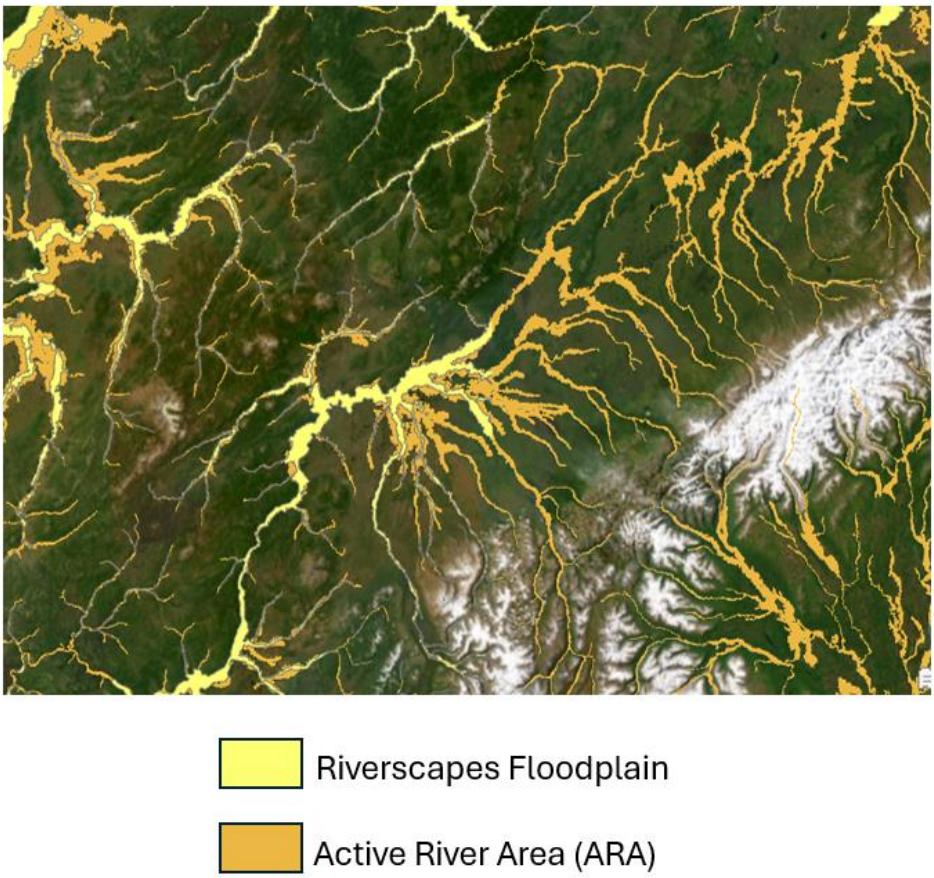
**Figure 3-16. The 2016 NLCD for Alaska (A) was updated with current and historic mining areas (B) to represent current land cover for the state.**




## Floodplains

Connections between a river and its floodplain are essential to the resilience of the system because floodplains allow for water storage, nutrient flushes, and create spatial and temporal feeding and breeding habitat (Pringle 2003). The connection can be interrupted by roads and levees, although this can be difficult to precisely measure because it depends in part on the intensity and depth of each flood event, or the return interval of the flood. We calculated a metric of floodplain naturalness to estimate the relative intactness and availability of the floodplain. To map floodplains, we combined the TNC delineated 30-m Active River Area (Anderson et al. 2022) with the Alaskan Riverscapes polygons (Whited et al. 2012).

**Figure 3-17. Example of floodplain extent.** The floodplain footprint included the TNC delineated 30-m Active River Area (Anderson et al. 2022) along with the Alaskan Riverscapes polygons (Whited et al. 2012).




## Floodplain Naturalness Index

After removing open water from the 100-year floodplain, we quantified the extent of four land cover categories (Table 3-8) in this zone using data from the 2016 NLCD augmented with surface mining extent. Land cover classes were weighted such that wetlands or natural forests had the highest positive influence and roads or permanent development had the highest negative influence, with agricultural lands in between. We did not include pasture and hay lands in the agriculture category as research has shown this land use is not strongly correlated with poor water quality (de Mello et al. 2018). Degree of naturalness was quantified using a weighted index:

*(1 * % High Intensity) + (0.75 * % Agriculture) + (0.25 * % Low Intensity)*

**Table 3-8. Land cover class assignments used in the naturalness indices.**

| Naturalness Category | NLCD 2016 Class (Value Code) |
|---|---|
| High Intensity | Low Intensity Developed (22), Medium Intensity Developed (23), High Intensity Developed (24), Mining (10) |
| Agriculture | Cultivated Crops (82) |
| Low Intensity | Pasture/Hay (81), Open Space Developed (21) |
| Natural | Open Water (11), Perennial Ice/Snow (12), Deciduous Forest (41), Evergreen Forest (42), Mixed Forest (43), Shrub/Scrub (52), Herbaceous (71), Woody Wetlands (90), Emergent Herbaceous Wetlands (95), Barren (31) |

The index ranged from 0 for a floodplain in completely natural cover to 100 for a completely developed floodplain. We transformed the raw index using the *bestnormalize* package in R and translated the floodplain naturalness values into our standard z-score classes. HUC-12s with urban areas or impacted by resource extraction had naturalness values less than "Average." However, no watersheds scored higher than "Average" because most of the state's land cover is intact and undeveloped, thus most watersheds have floodplains with extremely high naturalness values. We studied the distribution of naturalness values for all the watersheds that scored "Average" and manually assigned z-scores using the class breaks shown in Table 3-9. Figure 3-18 shows the final floodplain naturalness scores for HUC-12s in Alaska.

**Table 3-9. Assignment of high floodplain naturalness values to z-score classes for HUC-12s that initially scored "Average" for floodplain naturalness.**

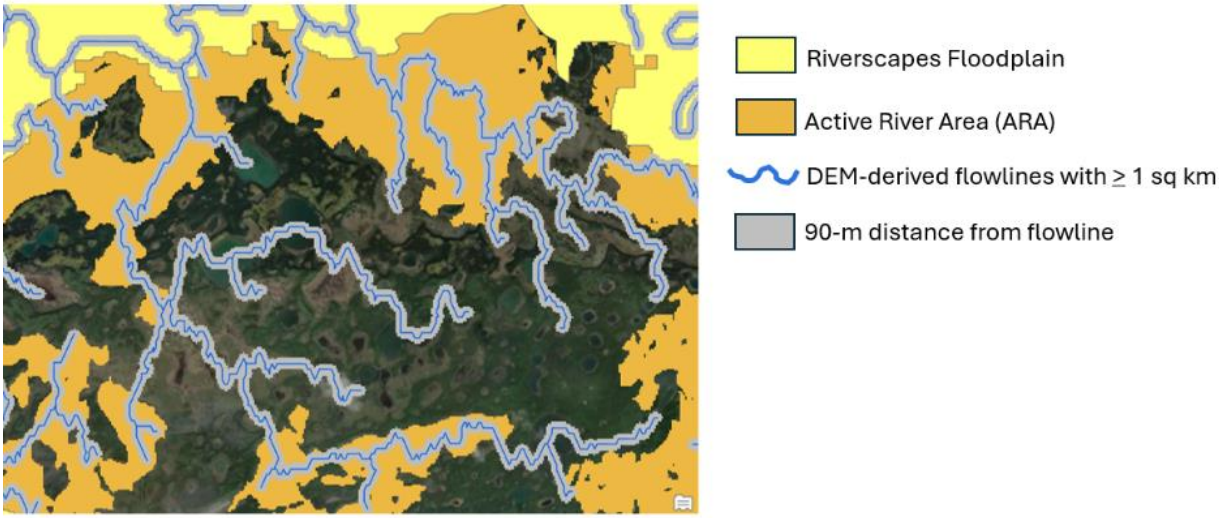
| Z-Score Class | Floodplain Naturalness Values |
|---|---|
| Far Above Average | 0 |
| Above Average | > 0 & < 0.05 |
| Slightly Above Average | ≥ 0.05 & < 15 |
| Average | ≥ 0.15 |

**Figure 3-18. Landcover naturalness index of the floodplain.** Watersheds in green have floodplains in more natural land cover while those in brown are dominated by mining, resource extraction, and/or urban land uses.

## Riparian and Floodplain Areas

Riparian zones contribute to freshwater resilience through their potential to attenuate the effects of precipitation changes (Paukert et al. 2021), dampen temperature rise impacts (Bowler et al. 2012), and retain sediments and nutrients that could degrade water quality (Kaufman et al. 2022). To map riparian areas, we applied a 90-m buffer to the MERIT 90-m DEM-derived streams and rivers with a minimum drainage area of one $km^2$. We then combined this riparian buffer with the floodplain footprint for an expanded "riparian and floodplain area" (Figure 3-19).

**Figure 3-19. Riparian area example.** The gray boundary denotes the 90-m riparian area around the blue DEM-derived flowlines which are shown on top of the floodplain areas in yellow and orange.

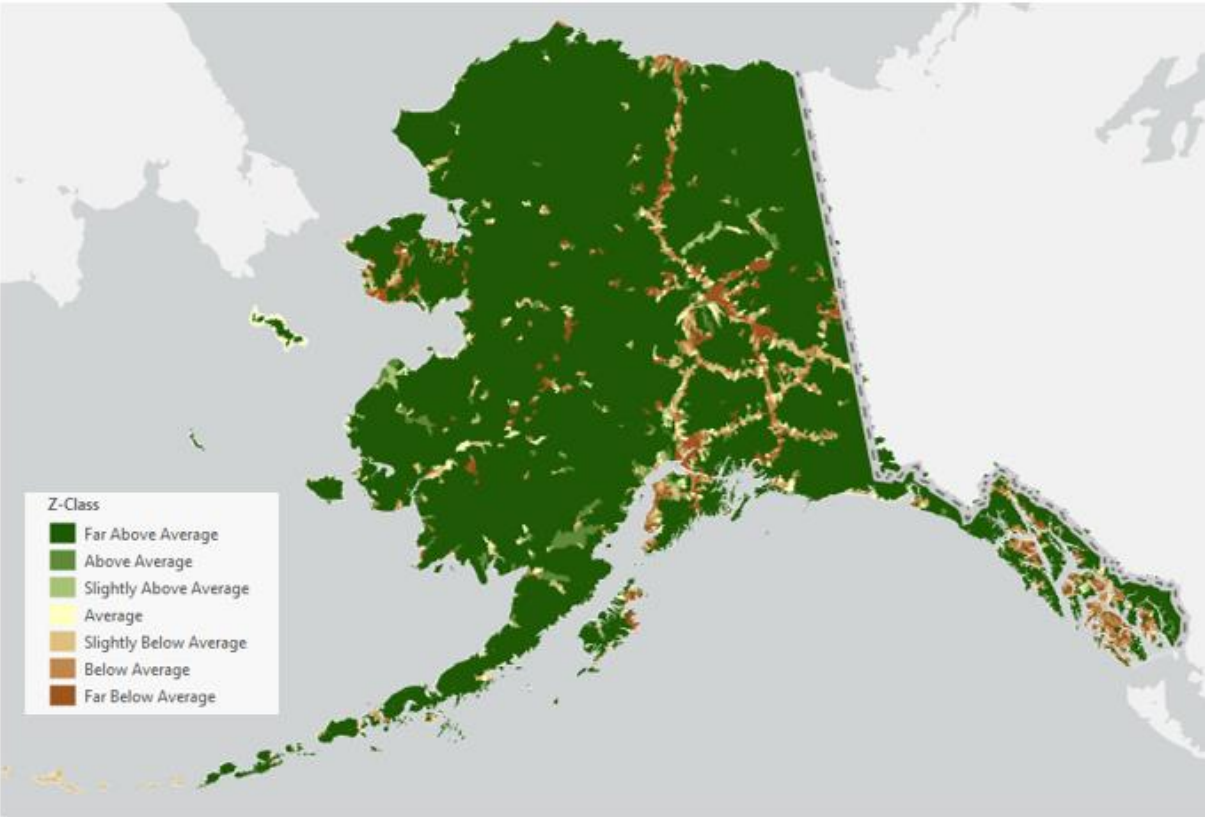



We classified land cover in the riparian-floodplain area in each HUC-12 into the four categories previously described and shown in Table 3-8. Using those categories, we calculated the land cover naturalness index in the same manner as described for the floodplain naturalness metric. Due to the state's largely intact land cover, we again had to manually assign z-scores to HUC-12s with very natural riparian and floodplain areas (i.e., units that scored "Average") using the values shown in Table 3-10 and mapped in Figure 3-20.

**Table 3-10. Assignment of high riparian and floodplain naturalness values to z-score classes for HUC-12s that initially scored "Average" for riparian and floodplain naturalness.**

| Z-Score Class | Riparian & Floodplain Naturalness Values |
|---|---|
| Far Above Average | 0 |
| Above Average | > 0 & < 0.05 |
| Slightly Above Average | ≥ 0.05 & < 10 |
| Average | ≥ 0.10 |

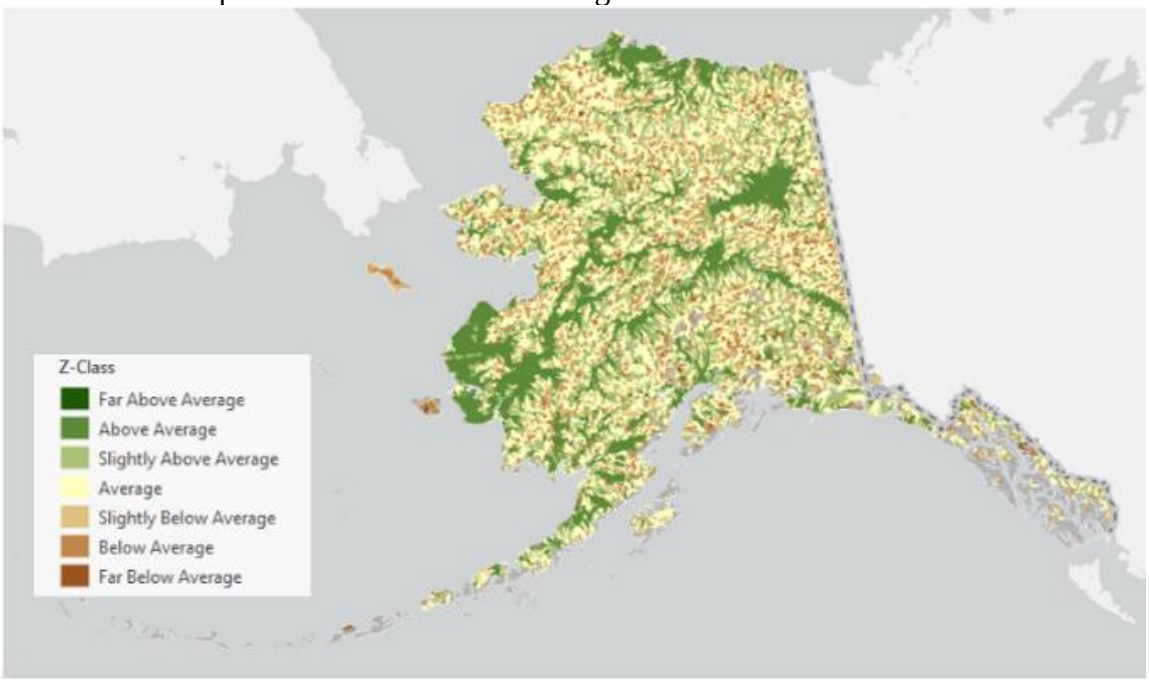
**Figure 3-20. Land cover naturalness index of the floodplain-riparian area.** Watersheds in green have floodplain and riparian areas largely in natural land cover while those in brown are dominated by resource extraction and/or developed land use.




## Integrating Floodplain-Riparian and Floodplain-Only Naturalness

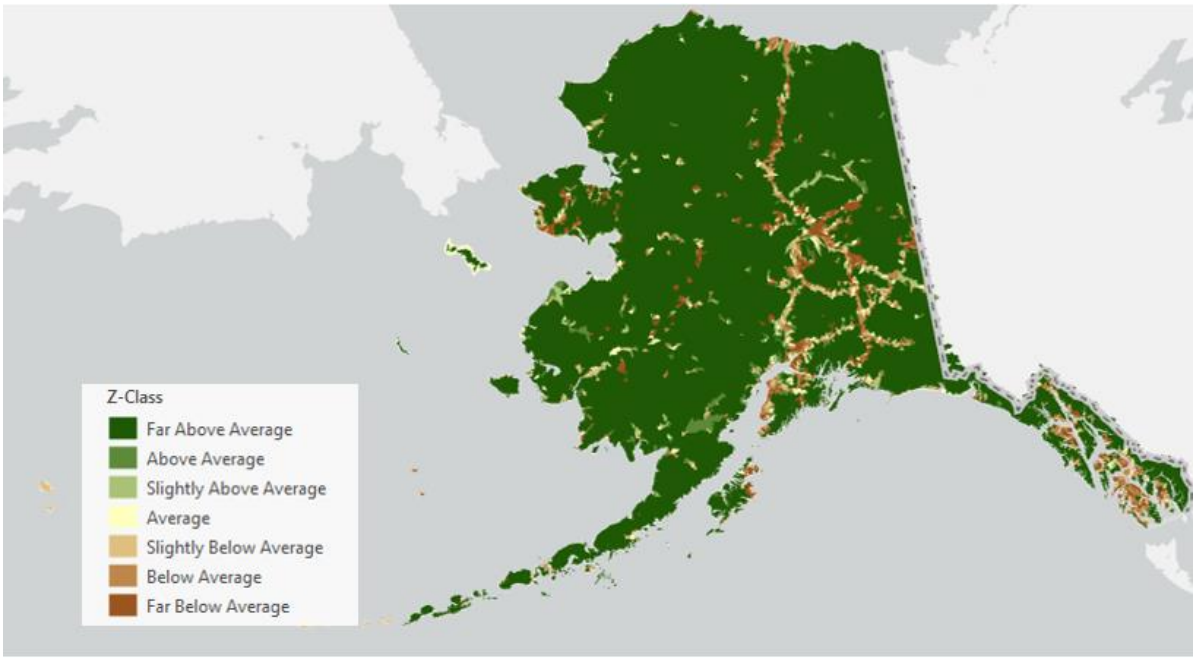
After reviewing the land cover naturalness indices for the two different extents (floodplain-only vs. floodplain-riparian), we established a set of rules to guide an integrated near river-stream naturalness score guided by whether floodplains were the more dominant feature in the HUC-12. We calculated the percentage of floodplain area in each HUC-12 and translated the percentages to z-scores (Figure 3.20).

**Figure 3-21. HUC-12 percent floodplain area.** Results reflect whether the percentage of the HUC-12 in floodplain is above or below average.




We then used the floodplain-only score (Figure 3-18) when the percentage of floodplain area was "Above Average" or "Far Above Average." For watersheds where floodplains were not a dominant feature (< 1 SD, in the "Slightly Above Average" or lower classes for floodplain percentage), we used the floodplain and riparian naturalness index score (Figure 3-20).

**Figure 3-22. Integration of floodplain-only and floodplain-riparian land cover naturalness.** Results reflect the integration rules and z-score adjustments described in the text.



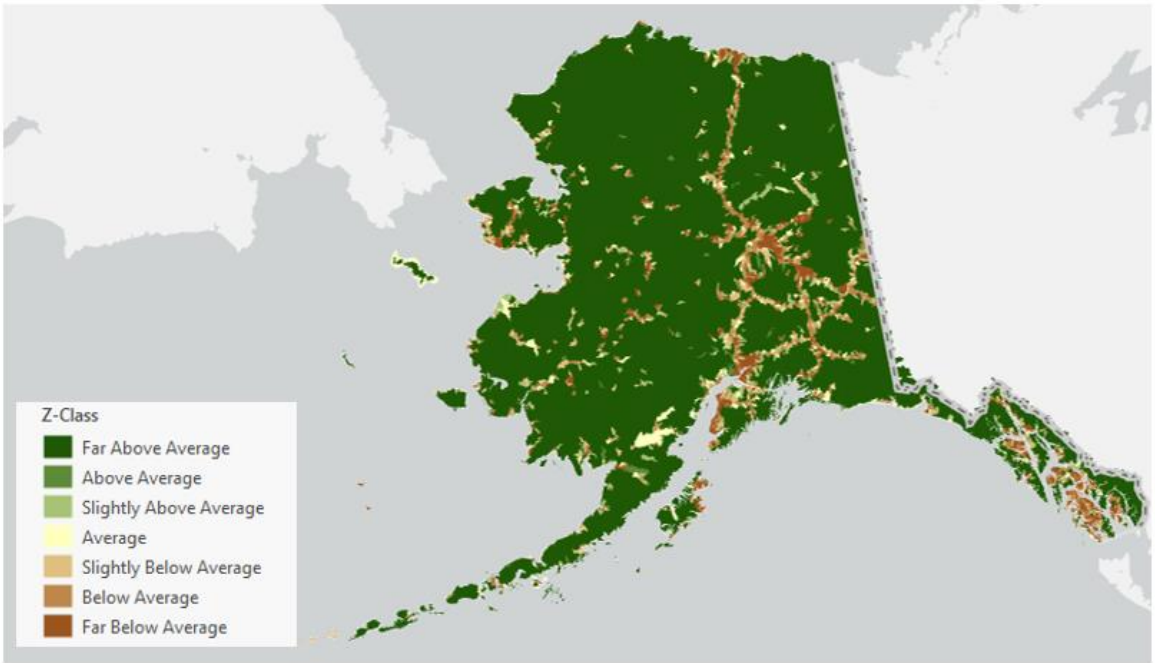

## Watershed Naturalness

To put the floodplain and riparian scores in context and to assess the degree of land cover degradation within the whole watershed, we calculated a watershed naturalness score for each HUC-12. We used the same methods as those described for the floodplain and riparian zones. Once again, we had to manually assign z-scores to units with very high watershed naturalness values (i.e., those that scored "Average") per the breaks in Table 3-11 and as mapped in Figure 3-23.

**Table 3-11. Assignment of high watershed naturalness values to z-score classes for HUC-12s that initially scored "Average" for watershed naturalness.**

| Z-Score Class | Watershed Naturalness Values |
|---|---|
| Far Above Average | 0 |
| Above Average | > 0 & < 0.01 |
| Slightly Above Average | ≥ 0.01 & < 0.06 |
| Average | ≥ 0.06 |

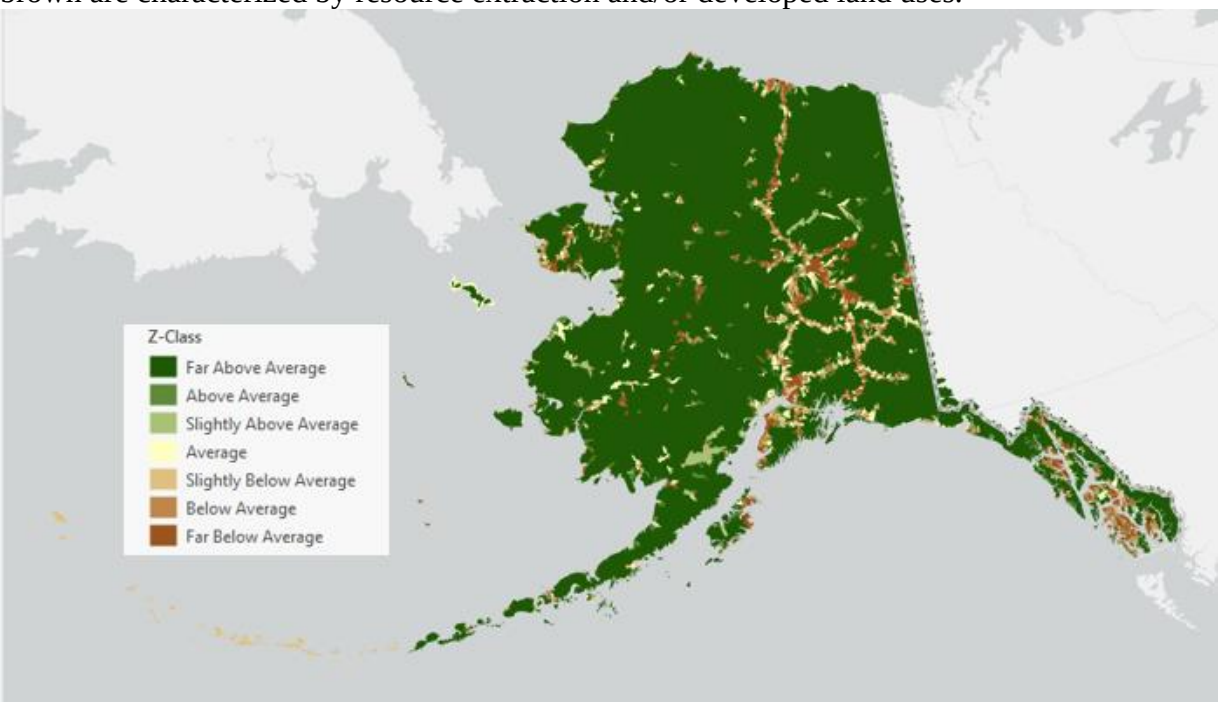
**Figure 3-23. Landcover naturalness index of HUC-12 watersheds.** Watersheds in green have more natural and intact land cover while those in brown are dominated by mining, resource extraction, and/or developed land uses.




## Integrating Floodplain, Riparian, and Watershed Naturalness

A visual comparison of the combined floodplain and riparian land cover naturalness index and the watershed naturalness index shows there are many watersheds where the two metrics are quite similar. However, there are also some areas where the two metrics tell a slightly different story in which riverine floodplains are intact, but their watersheds have some altered land cover or vice versa. To address the correlation between these two indices, we found that simply averaging the two z-scores appropriately balanced the interplay between these different scales. For example, a watershed with a very natural floodplain but a less natural watershed typically received an "Average" overall naturalness score (dependent on the actual z-scores for the two scales). A watershed primarily in natural cover and with a floodplain in natural cover received a high overall naturalness score. Our final integrated score (Figure 3-24) can be thought of as a watershed naturalness score (Figure 3-23) with more weight given to the floodplain and riparian zone (Figure 3-22) to reflect the importance of direct interaction with streams and rivers.

**Figure 3-24. Integrated watershed and floodplain-riparian naturalness scores.** The z-scores are the average of the watershed naturalness z-score and the floodplain only or floodplain and riparian naturalness z-score for each HUC-12. The floodplains and land cover of watersheds in green are more natural while the floodplain and land cover of watersheds in brown are characterized by resource extraction and/or developed land uses.




## *Water Quality*

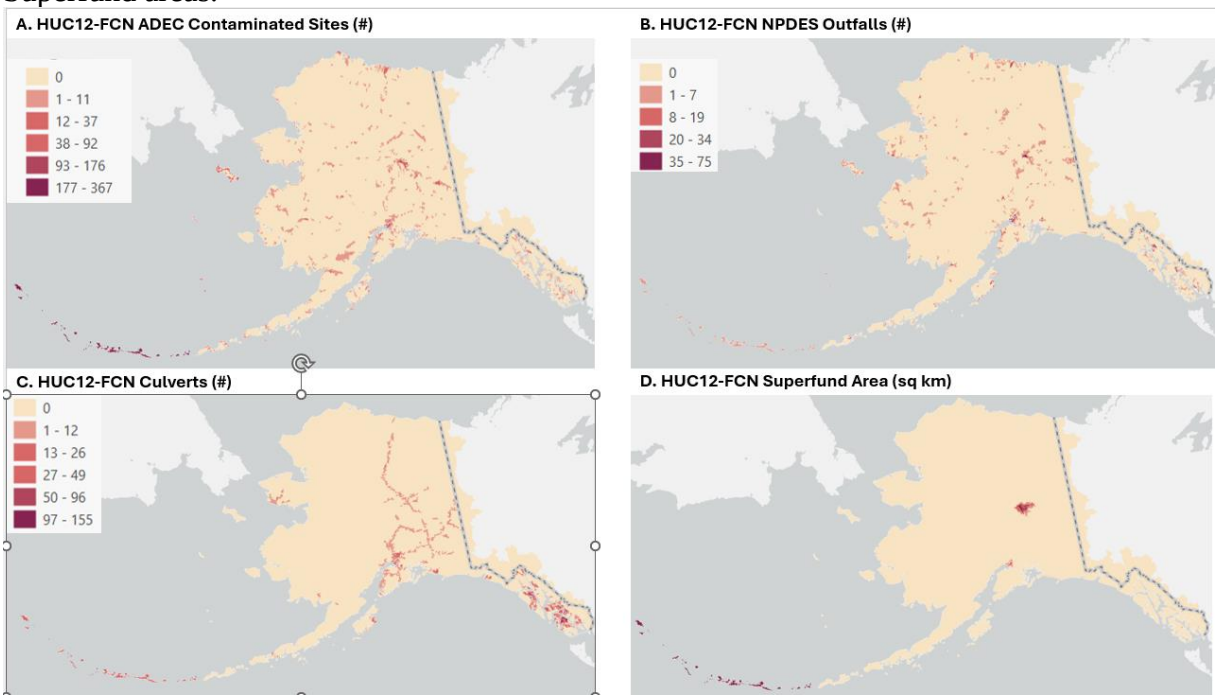
While streams and rivers in the conterminous U.S. face challenges from increasing levels of nutrients and sediment (Manning et al. 2020; Murphy 2020), nonpoint source pollution is less of a widespread problem in Alaska's waterways and largely confined to waters in the state's five major urbanized areas (ADEC 2020). The main water quality concerns in Alaska's rivers and lakes are toxic pollutants from mining, industrial operations, oil extraction, and transportation, as well as limited sanitation infrastructure in rural areas. Most recently, the release of metal ores into waterways from rapid permafrost thawing due to climate change is an increasing water quality concern for aquatic species and people in the Arctic region of Alaska.

To develop a water quality index for watersheds in Alaska, we adapted the methods used to assess water chemistry and sediment regulation in the Matanuska-Susitna basin of Alaska (Aho et al. 2020). First, we calculated a suite of variables for each HUC-12 to capture the most pressing water quality concerns in Alaska using readily available spatial data (Table 3-12, Figure 3-25).

**Table 3-12. Description and data sources of variables (n=10) used to assess water quality of HUC-12s in Alaska.**

| HUC-12 Variable | Description | Data Source(s) |
|---|---|---|
| Percent mining area | Percentage of watershed area in mine land | Historical and current ground disturbance resulting from surface mining across Alaska and Northwest Canada. Geist et al. (2017), updated 2024 |
| Percent agricultural area | Percentage of watershed area in pasture/hay (class 81) and cultivated crops (class 82) | 2016 NLCD |
| Percent impervious/urban area | Percentage of watershed area in NLCD low, medium, and high intensity development (classes 22, 23, 24) | 2016 NLCD |
| Density of pollution sites | Count of contaminated sites (TRI, Superfund) and NPDES outfalls /watershed area | Alaska Regulated Contaminated Sites (ADEC 2025), TRI and Superfund *Sites restricted with query to select Active and Status = Cleanup Complete with Institutional Controls, NPDES Outfalls Regulated Facilities (USEPA 2022) |
| Percent Superfund area | Percentage of watershed area designated as Superfund land | USEPA Superfund Site Boundaries from ADEC 2025 *Sites restricted to state of Alaska |
| Percent 303(d) impaired water bodies (areal extent) | Percentage of watershed area in impaired inland waterbodies (harbors and bays excluded) | ADEC 2024 with manual edits to add two recently listed segments: Tributary Creek and Boulder Creek |
| Density of 303(d) impaired streams/rivers (linear) | Length (km) / watershed area ($km^2$) | ADEC 2024 |
| Density of roads and railroads | Length (km) / watershed area ($km^2$) | TIGER/Line 2024 |
| Density of Culverts | Count of culverts /watershed area | BarrierType = 'Assessed road-related barrier' (SARP 2024) |
| Rusting Risk index | See description below in text | See description below in text |

**Figure 3-25. Selected water quality variables.** Maps of some of the input water quality index variables: A) ADEC contaminated sites, B) EPA NPDES outfalls, C) culverts, and D) Superfund areas.




Recent research has documented the rusting of streams and small rivers in Alaska's Brooks Range over the past ten or so years. Researchers hypothesize that impacted waterways turn orange from the mobilization of metals due to rapid permafrost thaw (O'Donnell et al. 2024). These orange rivers have poor water quality parameters (low pH, high turbidity, high sulfate and iron concentrations) and dramatically lower macroinvertebrate diversity and fish abundance compared to non-impacted reference streams. In addition to ecological impacts, rusting may limit the use of stream and river water by local communities that depend on it. The latest studies suggest the Alaskan waterways most at risk from rusting are those located in the Brooks Range, particularly the Kobuk River, Wulik River, Salmon River, and tributaries within the Kobuk Valley National Park.

To assess the relative risk of rusting in streams and rivers for watersheds in the Brooks Range, we first selected HUC-12s that intersected the Brooks Range terrestrial ecoregion (Figure 3-26). To account for watersheds with only a small amount of their area in the Brooks Range, we calculated the proportion of each HUC-12 that is in the Brooks Range ecoregion. To identify areas with deeper permafrost melt and thus additional activation of subsurface water flow paths, we calculated a projected change in the depth of the seasonally thawed layer above permafrost using the active layer thickness model of 2019 versus 2049 from the Geophysical Institute Permafrost Lab model (University of Alaska, Fairbanks, 2011). We then calculated the mean permafrost depth change by 2049 for each HUC-12 to identify those units predicted to have larger amounts of thawed subsurface water (Figure 3-26). After examining spatially explicit data on orange streams (Koch et al. 2023), we found that rusting appears to be limited to headwaters and tributaries, size class 20 or smaller in our size classification. Thus, we

calculated the percentage of each watershed's total flowline length (> 2 $km^2$ drainage area) that was less than or equal to size class 20. We then multiplied this percentage by the proportion of the watershed that is in the Brooks Range. Finally, to calculate the rusting risk index, we multiplied the depth risk class (Figure 3-26) by the percentage of flowlines streams and small rivers, adjusted for watershed proportion area in the Brooks Range (Figure 3-27).

**Figure 3-26. Assignment of estimated mean permafrost depth change by 2049 (Univ. of AK, Fairbanks 2011) to five classes using natural breaks for HUC-12 watersheds that intersect the Brooks Range terrestrial ecoregion (black outline).**

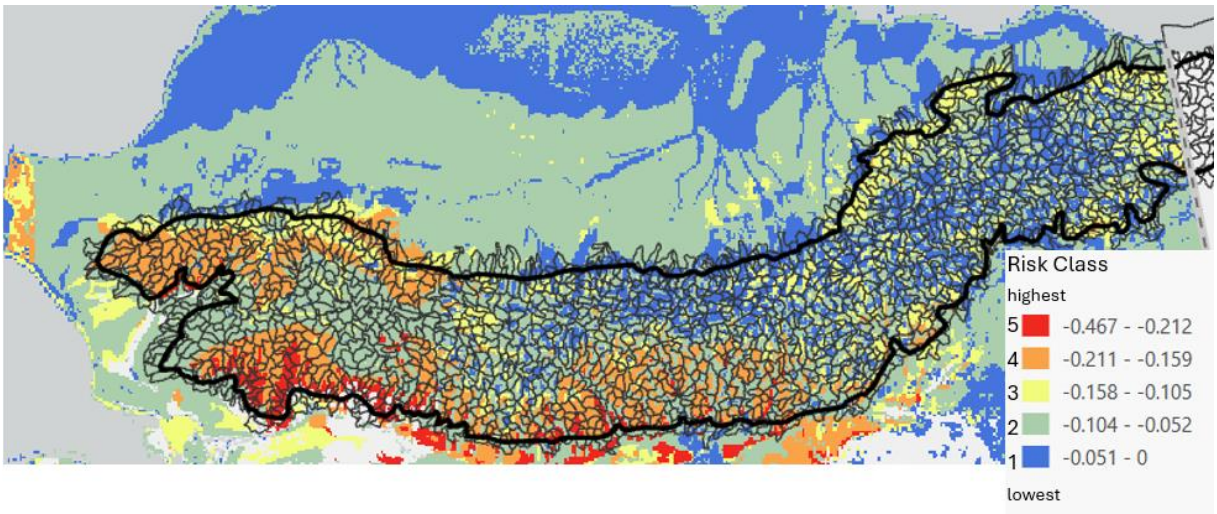
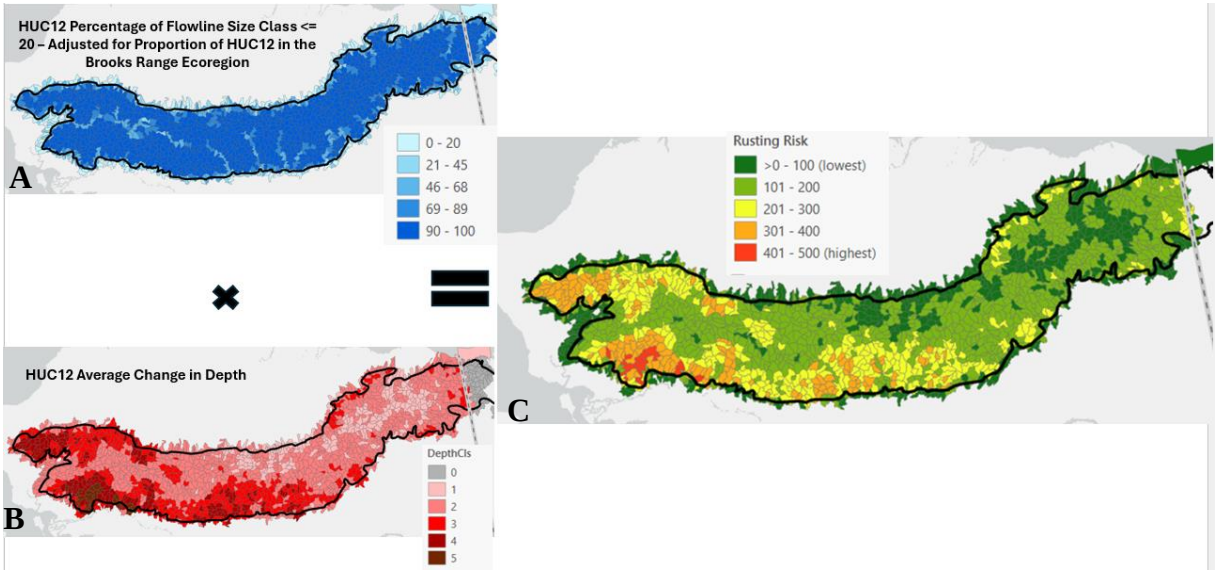



**Figure 3-27. Calculation of stream rusting risk index for HUC-12 watersheds that intersect the Brooks Range terrestrial ecoregion (black outline).** A) The percentage of flowlines in size class 20 or smaller, adjusted by the proportion of the watershed in the Brooks Range, and B) the depth class were multiplied to yield a relative measure of rusting risk that is shown in panel C.



## *Water Quality Index*

To develop an index of water quality, we first used Spearman's rank-order correlation coefficient *p* to determine if any of the HUC-12 input variables described in Table 3-12 exceeded a correlation threshold of 0.70 per the methods in Aho et al. (2020). As none of the input water quality variables were highly correlated (p > 0.70), we calculated summary statistics for each of the ten input variables and used those values to calculate a Water Quality Index (WQI) for each watershed based on the revised Index of Catchment Integrity (ICI) formula in Aho et al. (2020, Eq. 1) where *w* refers to the HUC-12 watershed, $s_{j,w}$ is the value for the *jth* variable or stressor across all watersheds, $s_{j,wmax}$ is the worst possible value (maximum value across all watersheds in the state) and $n_{i,w}$ is the number of stressors associated with the *ith* variable that could occur in watershed *w*. The maximum number of stressors was nine for all watersheds except for those in the Brooks Range, which had ten due to the rusting risk index.

**Equation 1. Formula used to calculate an index of water quality for HUC-12s in Alaska from Aho et al. (2020).**

$$WQI_{i,w} = \frac{\Sigma_{j=1}^{n_{i,w}} \left[1 - \left(\frac{s_{j,w}}{s_{j,wmax}}\right)\right]}{n_{i,w}}$$

Most watersheds had few if any water quality stressors and thus had the highest or best WQI value of 1 (Figure 3-28). We translated the resultant water quality index scores to z-scores, where "Average" values indicated watersheds with no water quality stressors and WQI values of 1. As watersheds in Alaska are largely intact and undeveloped, a WQI score of 0.92 was "Below Average" in Alaska even though 0.92 would be an excellent score and greater than "Average" for a watershed in the conterminous U.S.

**Figure 3-28. Water Quality Index (WQI) for HUC-12 watersheds.**

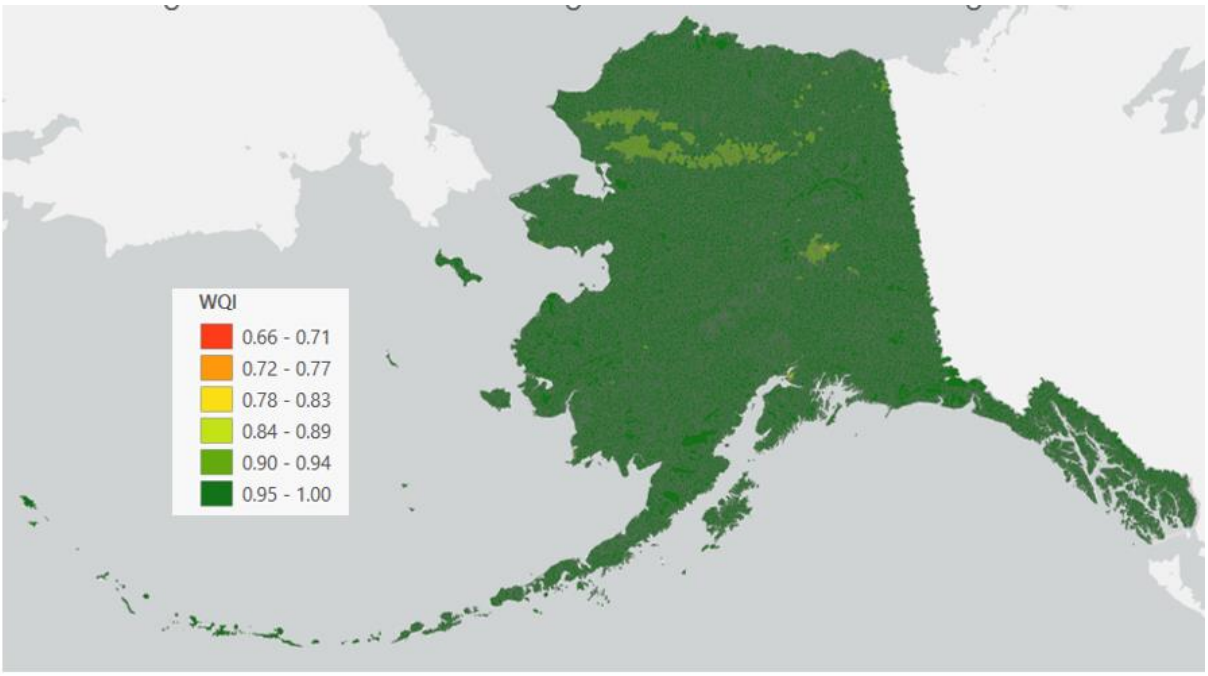
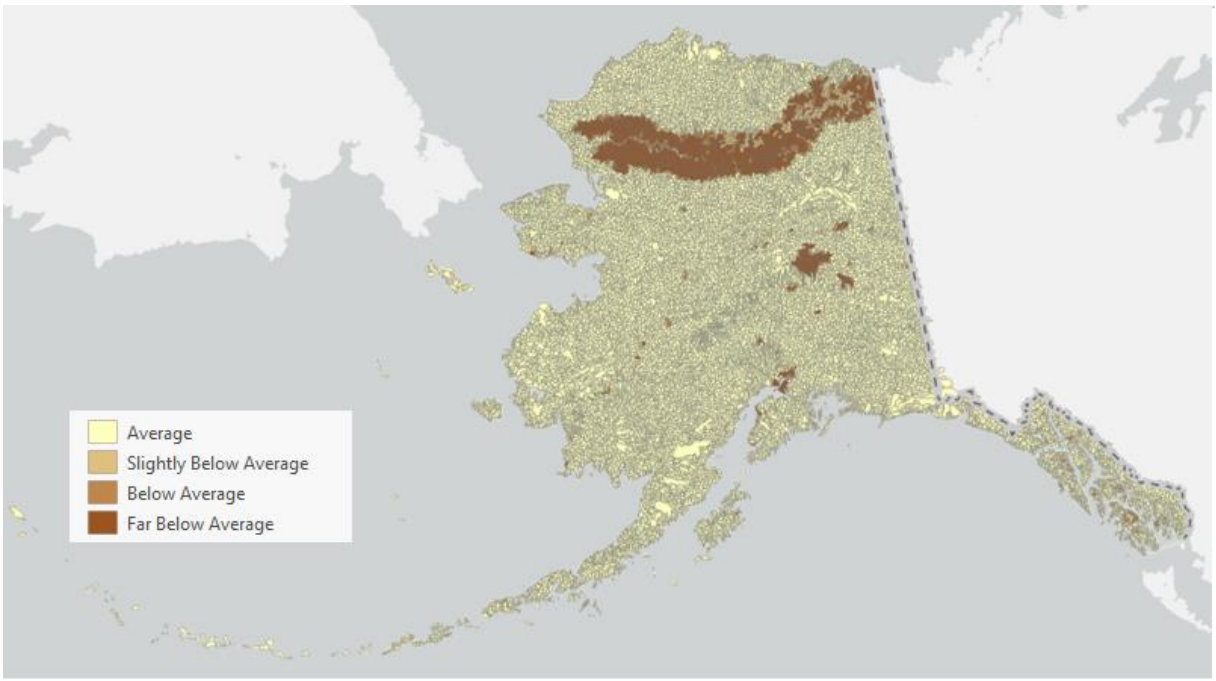


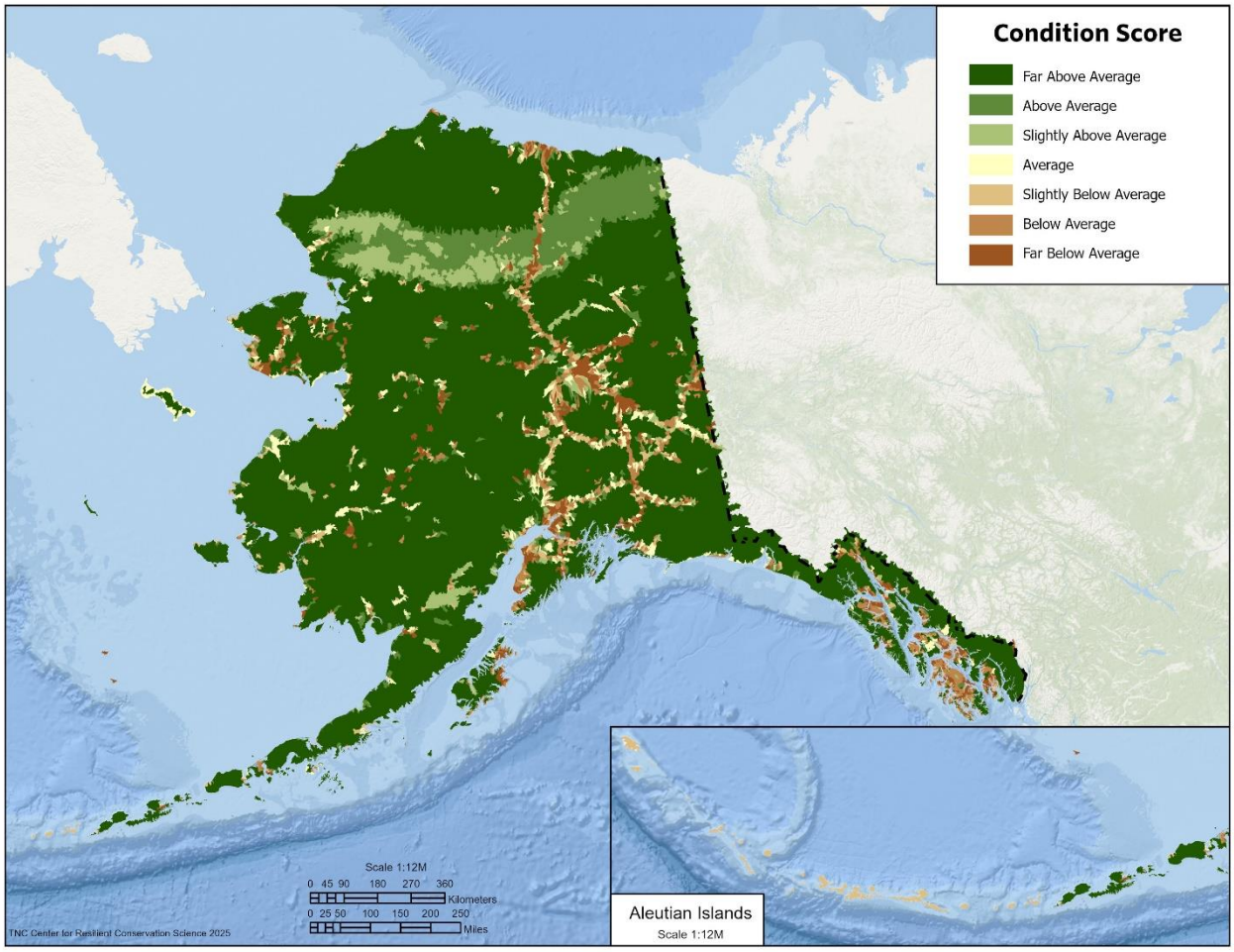

**Figure 3-29. Water Quality Index score.** This map shows the WQI values translated to z-score classes. Watersheds in yellow are expected to have good water quality as they have no significant values for the stressors listed in Table 3.12.



## *Integration of Condition Metrics*

As many of Alaska's watersheds are in pristine condition, we used the following rules to combine the final naturalness and water quality scores. If a watershed had an "Average" z-score for water quality (i.e., no water quality stressors present), we only used the final naturalness score. If a watershed had a water quality z-score less than "Average," we combined the water quality and naturalness z-scores with water quality weighted 33% and naturalness weighted at 66%. Figure 3-30 shows the result of this integration and the impact of incorporating the water quality scores can be seen in the watersheds of the Brooks Range, major urban areas, and transportation corridors.

**Figure 3-30. Condition score.** This map shows the integrated condition scores after combining the water quality and naturalness z-scores as described in the text.

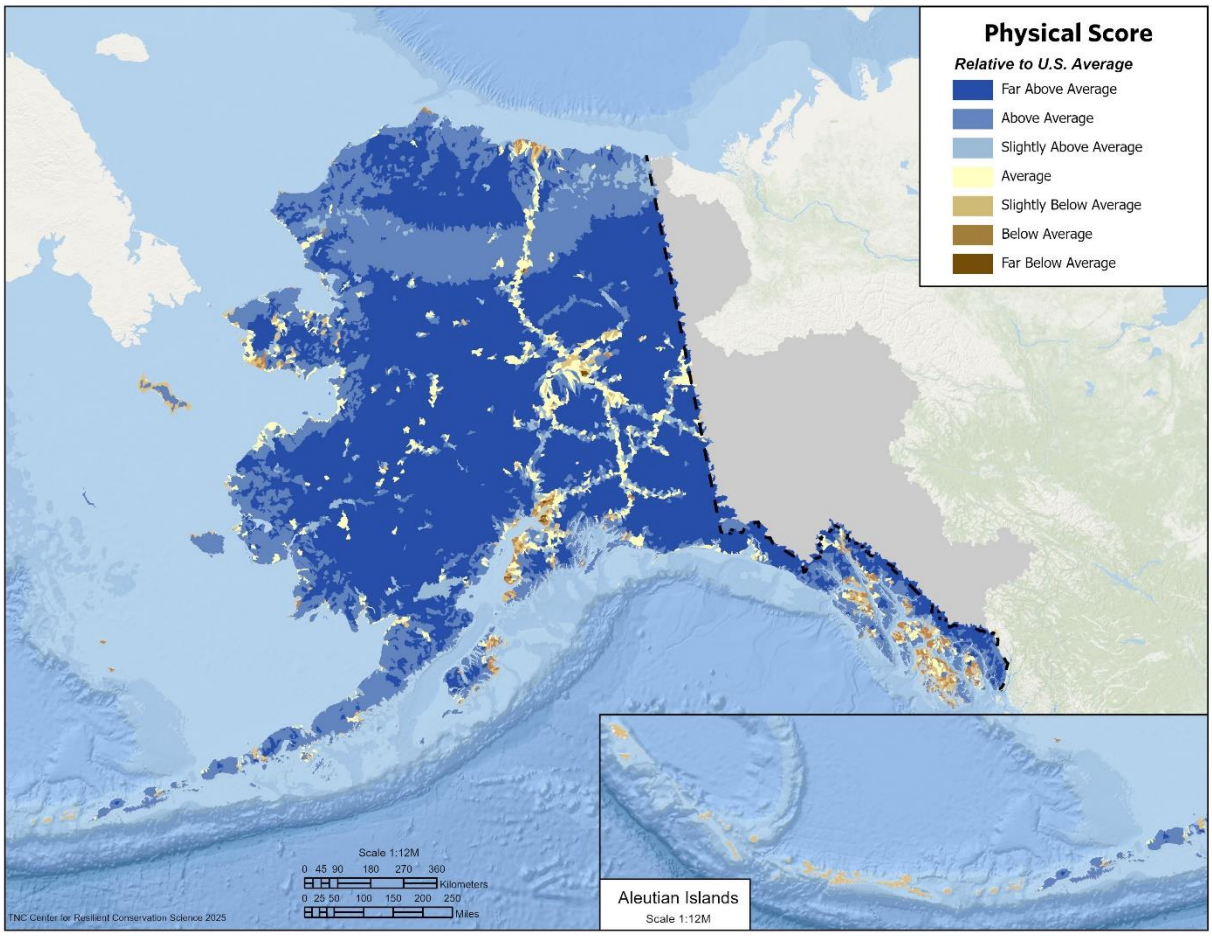


## Integrated Physical Score

To derive a final physical score (Figure 3-31) for each HUC-12 watershed, we combined the connectivity score (Figure 3-15) and the condition score (Figure 3-30) with equal weights (Anderson et al. 2024).

*Physical Score = (1*Connectivity + 1*Condition) / 2*

**Figure 3-31. Physical score.** This map shows the final integration of the connectivity score and the condition score.



# Water Score

The water score was designed to estimate the availability of ample unaltered water to rivers and streams. In the conterminous U.S. freshwater resilience analysis, we divided the country into two zones, arid and humid, based on an aridity index (Zomer et al. 2008) and our methods to calculate the water score differed by climatic zone to reflect large water availability differences between arid and humid freshwater ecoregions. In humid ecoregions where surface water was abundant and streams and rivers were predominantly perennial, the water score was driven primarily by anthropogenic hydrologic alteration from dams, impervious surfaces, and other land use factors which alter the natural flow regime. In arid to xeric regions, where surface water was limited and often intermittent, the water score integrated anthropogenic hydrologic alteration, but also included strong emphasis on groundwater resources, groundwater alteration, and enduring surface topographic features that could store water.

Alaska is a non-arid region (Zomer et al. 2022; Tabari 2020; Beck et al. 2018) with streams and rivers that are dominantly perennial (>97%, USGS 2023) reflecting the state's cold climate and consistent snowmelt and groundwater. Surface water is abundant, with approximately 43% of Alaska's surface area covered by wetlands, and other open water (waterbodies or wide rivers) covering approximately 14% of the state's area (EPA: Hall, 1994). Groundwater is abundant, with Alaska having the greatest groundwater resources of any state in the United States (Alaska Hydrologic Survey – Division of Mining, Land, and Water, 2025). Groundwater extraction in Alaska is not currently recognized as causing significant widespread ecological harm as extraction levels are relatively low, with only about 63 million gallons per day withdrawn statewide (Alaska Department of Environmental Conservation, 2025). Most use is concentrated in Anchorage, Fairbanks, the Matanuska-Susitna Borough, and the Kenai Peninsula where localized impacts are correlated with development and settlement locations. Agricultural use is minimal, less than 1% of groundwater is used for agriculture (Alaska Department of Environmental Conservation, 2025).

Water is expected to remain abundant in Alaska. Future climate projections predict an increase in precipitation across Alaska with annual average precipitation projected to increase by at least 10% across all of Alaska by the middle of this century (NOAA, Kunkel, et al. 2022). Stream flow simulations using downscaled climate models predict runoff increases for most of the state, with reductions only in parts of Southeast Alaska which are changing to a rain-driven hydrograph (Mizukami et al. 2022). Permafrost melt has caused the size and distribution of lakes and wetlands to change as they regain connections to active ground water (Sidik, 2025; Web et al. 2022), and some streams are receiving greater groundwater contributions which increase water availability (Jorgenson et al. 2025). The dynamics of gaining and losing streams and related changes in surface-groundwater interactions is an area of emerging research as permafrost and glaciers melt and precipitation increases (Callegary 2013; Walvoord 2016; Koch et al. 2022; Sjöberg et al. 2021; Liljedahl et al. 2020). In the future, however, it is reasonable to expect more water will be interacting with the shallow and deeper groundwater systems that ultimately feed downstream rivers.

Given the abundance of available water, we treated the Alaskan hydrologic setting as similar to the humid zone of the conterminous U.S. where we assumed water was potentially available but may not flow according to the natural hydrologic regime due to hydrologic alteration from dams and other land use factors.

# Flow Alteration

Flow is considered the master variable to sustain ecological integrity for rivers and streams (Poff et al. 1997). A typical Alaska stream experiences low flows from December through March, peak flows when snow melts and the lakes and streams thaw during breakup in May-June, lower summer flows in July and August, secondary peak flows produced by rainfall in September-October, and declining flows in November (Alaska Hydrologic Survey – Division of Mining, Land, and Water, 2025).

Flow shapes channel structure and substrate composition. It drives sediment transport, buildup and erosion, altering habitat structure and availability. High and low flows can flush or concentrate nutrients influencing water quality and food webs. Some freshwater species rely on specific flow conditions to cue spawning and migration and certain natural flow patterns and conditions are necessary for successful egg development, feeding, and shelter throughout the year.

We accounted for anthropogenic alterations to the natural flow regime by developing an index of hydrologic alteration based on the EPA hydrologic regulation index method developed for Alaska' s Matanuska-Susitna basin (Aho et al. 2020). This hydrologic regulation index had five inputs: density of canals, density of culverts, percent agriculture, percent impervious, and density of reservoirs as a proxy for dam storage volume. We replicated these inputs for each HUC-12 unit for the state as described in the following section.

## *Flow Alteration Metrics*

### Density of Ditches, Canals, and Pipelines

Canals, ditches, and pipelines alter the natural flow paths and are primarily used to divert water for human uses. We extracted ditches, canals, and pipelines from the NHD High resolution flowlines, summarized the length (km) of each feature in each HUC-12, and then calculated their density as length divided by area in $km^2$ (Figure 3-32).

### Culvert Density

Culverts are located where streams and roads intersect. At these intersections, flow is constricted, flow and sediment dynamics altered, and many culverts become partial or complete barriers impassable to aquatic biota. To evaluate the location and impact of culverts, we used the HUC-12 culvert density metric described for the water quality index (Table 3-12, Figure 3-33).

**Figure 3-32. Density of ditches, canals, and pipelines.** This map shows the density (km/km$^2$) of ditches, canals, and pipelines in each HUC-12 watershed.

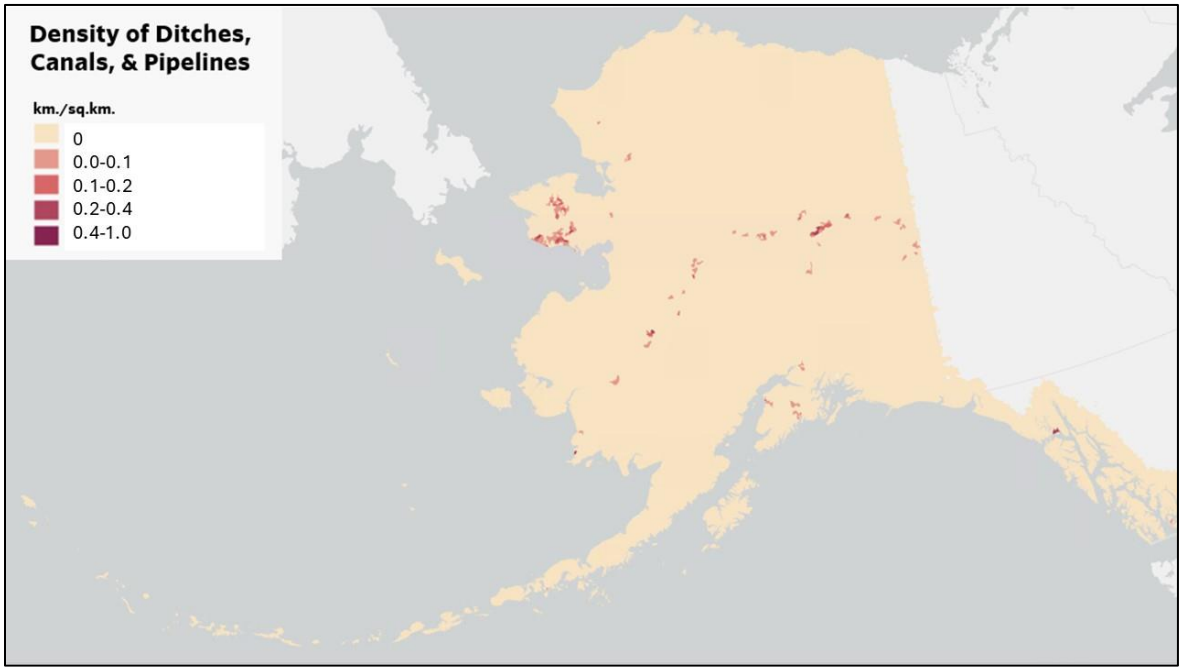
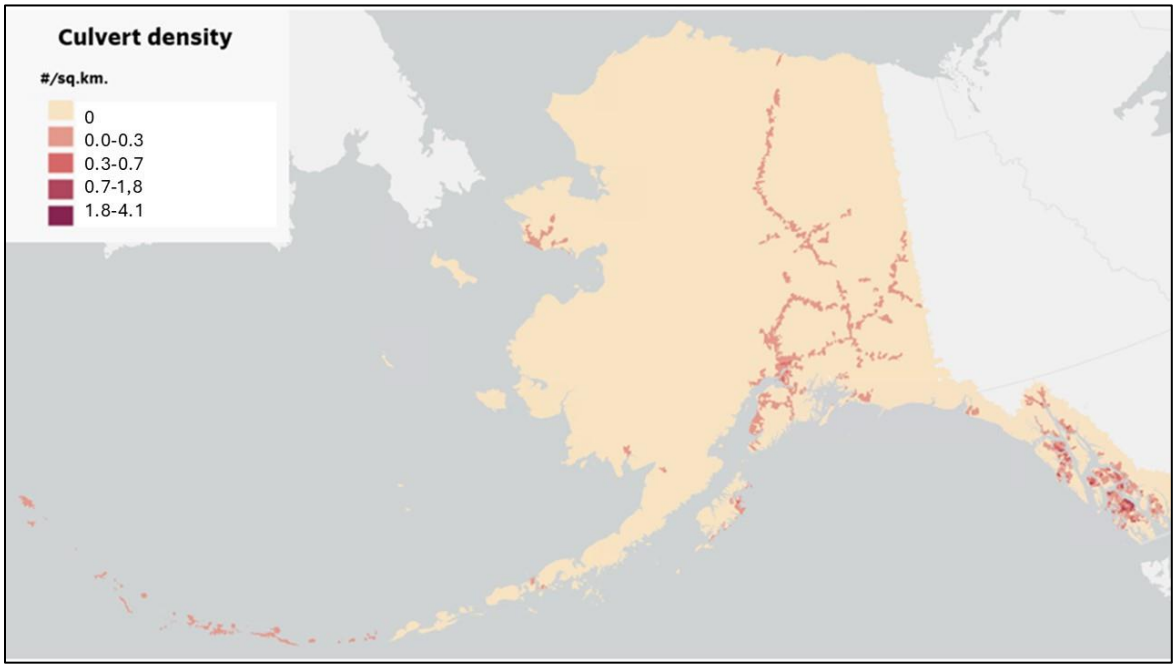



**Figure 3-33. Culvert density.** This map shows the number of culverts per area (km$^2$) of each analysis unit.



## Percent Crops

Water used for agriculture can be an important source of hydrologic alteration. We did not have information on irrigation, but as a proxy for potential agricultural water use, we calculated the percentage of 2016 NLCD row crops in each HUC-12 unit (Figure 3-34).

**Figure 3-34. Percent row crops.** This map shows the percentage of each watershed in row crop cover (NLCD 2016).

## Percent Impervious

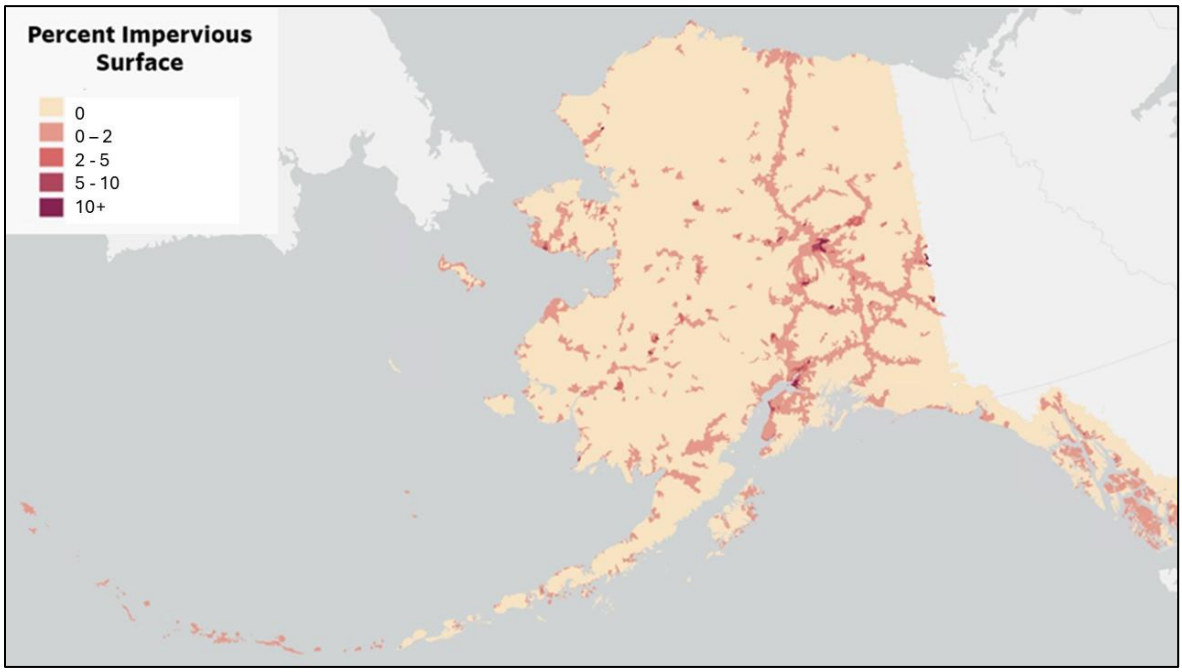
We used the area of developed land cover (NLCD 2016) and the augmented mine area (see Condition section) to calculate an estimate of imperviousness for each HUC-12. Impervious surfaces prevent infiltration leading to higher and faster peak flows during storms, reducing groundwater recharge, and increasing the risk of flooding (CWP 2003). Impervious surfaces are associated with human settlements and may also serve as a proxy for possible groundwater and surface water extraction.

The NLCD documentation suggests a range of imperviousness values for each of the developed land cover classes. We assigned each NLCD developed land class the midpoint of its imperviousness range (Table 3-13), and then summarized the value of the land cover pixels in each HUC-12 (Figure 3-35).

**Table 3-13. Imperviousness values assigned to the NLCD land classes and mine land.**

| Land Cover Class | Midpoint Imperviousness Value (%) |
|---|---|
| High Intensity Developed, Mines | 90 |
| Medium Intensity Developed | 65 |
| Low Intensity Developed | 35 |
| Developed Open Space | 10 |
| Mining Area | 90 |

**Figure 3-35. Percent impervious surface.** This map shows the percent impervious surface estimated within each HUC-12 based on developed land cover and mined land.



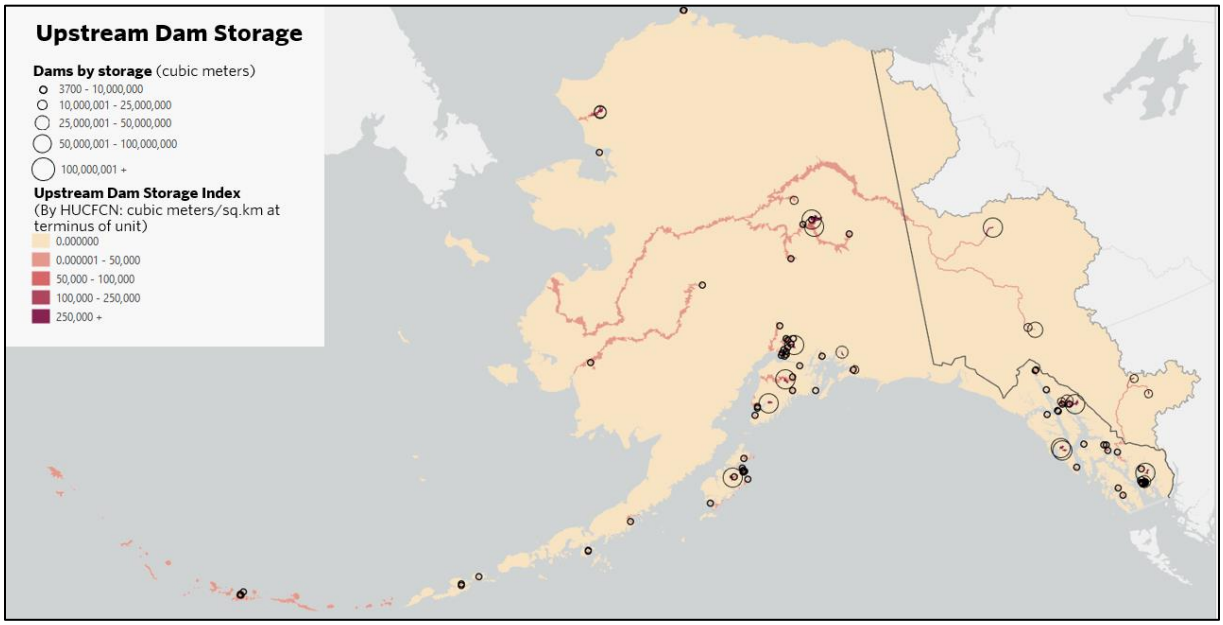

## Upstream Dam Storage Capacity

The volume of water that dams are capable of storing is recognized as a key measure of the degree of hydrologic alteration in rivers and streams (Grill et al. 2019; Thornburgh et al. 2018). High upstream dam storage means that a large portion of a river's annual flow is captured and controlled by upstream dams and reservoirs. This storage and control may have a detrimental effect on freshwater water ecosystems as it can significantly alter seasonal patterns of flow, reduce flow variability, and suppress natural flood pulses. The volume of water stored behind dams was the strongest predictor of overall hydrologic alteration as measured by changes from reference condition in over 40 flow metrics at gages for streams and rivers in the conterminous U.S. (McManamay et al. 2022). Similarly, upstream dam storage volume was found to be the most influential variable associated with severe alteration to flood flows and riparian and floodplain wetting for rivers in the U.S. (Fitzhugh & Vogel, 2019). A recent study of Arctic rivers documented pre vs. post dam impacts on the Yukon River in Alaska and found the Yukon to have a medium-average degree of flow alteration (Patro et al. 2023).

To assess the upstream dam storage capacity of Alaskan rivers and streams, we compiled available information on the storage capacity of all dams, including 99 in Alaska (National Inventory of Dams USACE 2025) and five in Canada (Lehner et. al. 2024). For the purposes of this analysis, we assumed that the other dams were run of the river dams that don't store water and where possible, verified this to be the case via research, especially for the seven dams in British Columbia that are upstream of Alaskan rivers. Of the 143 total dams in our analysis area, 73% had a reported storage volume. To accumulate the dam storage upstream of each reach, we converted the U.S. and Canadian dam storage values to cubic meters, and used this as the "weight" variable on "pour points" in a raster flow accumulation with the 90-m DEM flow direction grid. We then divided the accumulated upstream storage by the upstream drainage area of each pixel to estimate the ratio of dam storage to upstream drainage area. Higher ratios indicate that a larger proportion of the total expected flow could be stored and controlled by upstream dams which would thus have a larger negative ecological effect.

For each HUC-12, we extracted the dam storage index value corresponding to its most downstream river pixel (i.e., watershed outlet) to represent the ratio of dam storage to upstream drainage area at the terminus of each HUC-12. If no river occurred in the HUC-12, the storage index was calculated as the total dam storage on streams in the HUC divided by the area ($km^2$) of the HUC (Figure 3-36).

**Figure 3-36. Upstream dam storage.** This map shows the HUC-12 units by the river outlet's total upstream dam storage in cubic meters per square kilometers of upstream drainage area.



## *Water Score: Flow Alteration*

To develop an integrated flow alteration index, we used Spearman's rank correlation coefficient to ensure none of the input variables were highly correlated ($p > 0.70$) and then applied the summation formula for the EPA's Index of Catchment Integrity (ICI, Aho et al. 2020). See Equation 1 in the Water Quality section of this report.

We modified the formula to give more weight to certain variables based on the CONUS-wide Hydrologic Alteration Index (HAI, McManamay et al. 2022) which provides a relative importance value for each variable. To develop the final weights for the five input variables in our model, we divided each variable's HAI importance value by canal/ditch/pipeline density scores (the lowest HAI variable importance score). For example, the HAI importance score for impervious surface percentage was 0.354, which we divided by 0.088 to yield a weight value of 4. Table 3-14 shows the HAI importance values and the weights we assigned to variables in our flow alteration model.

**Table 3-14. Determination of variable weights to assess flow alteration in HUC-12 watersheds based on HAI variable importance (McManamay et al. 2022).**

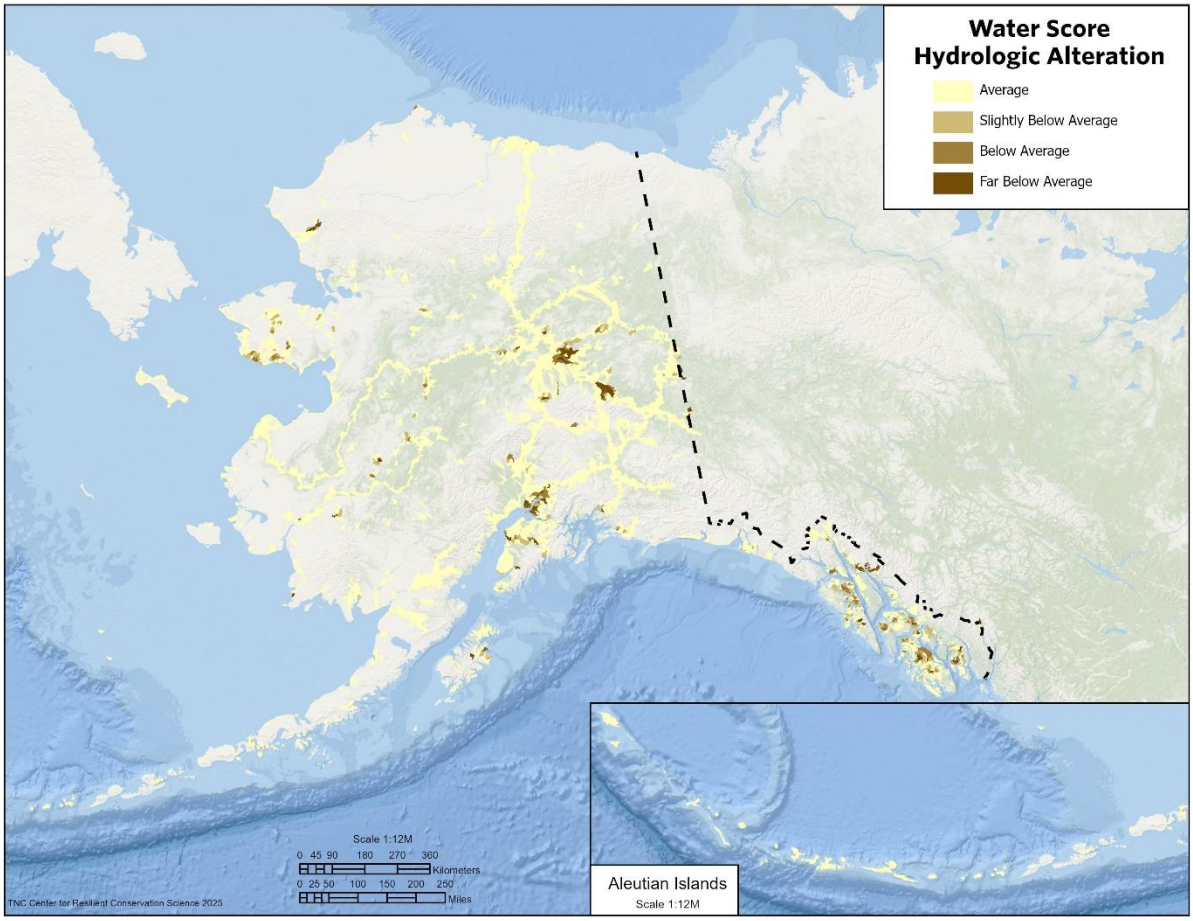
| Variable | HAI Importance | Flow Alteration Model Weight | Flow Alteration Model Component (%) |
|---|---|---|---|
| Canal/ditch/pipeline density | 0.088 | 1 | 5 |
| Percent cropland* | 0.157 | 2 | 10 |
| Culvert density | 0.188 | 2 | 10 |
| Percent impervious surface* | 0.354 | 4 | 20 |
| Dam storage relative to upstream drainage area ($m^3/km^2$) | 1 | 11 | 55 |

*Reporting max scoring variable in category for agriculture and urban areas where McManamay et al. (2022) included more than one variable.

We transformed the resultant values to approximate a normal distribution and then converted them to z-scores. This resulted in all units being classified as average or below-average as few had high impacts. HUC-12s that scored below-average had high dam storage ratios and/or large amounts of impervious surface, culverts, ditches, or cropland. Most HUC-12s had no hydrologic impacts per the variables measured and scored as average.

Because the water scores were so good, for integration with the physical score we used the flow alteration score only if the HUC-12 had some measured hydrologic alteration. This essentially removed most of the average (i.e. unaltered) HUC-12s from the group (Figure 3-37).

**Figure 3-37. Water Score: flow alteration.** This map only shows HUC-12 units having flow alteration based on the variables measured in this analysis. Pristine units with no measured flow alteration are not shown.



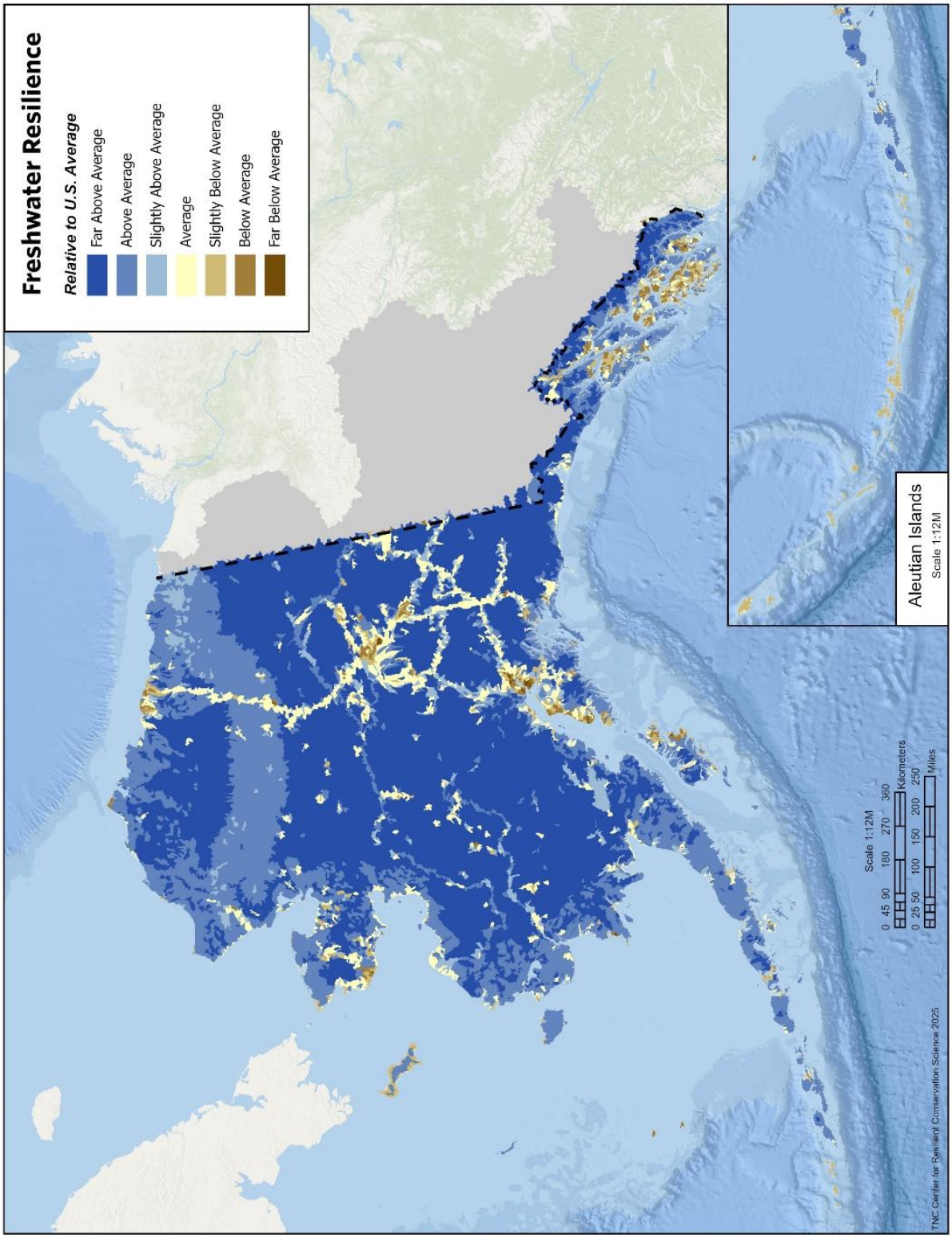
# Integrated Freshwater Resilience Score

We calculated a resilience score for each HUC-12 by taking a weighted average of each unit's physical score (Figure 3-31) and water score (Figure 3-37). Following the approach used for humid ecoregions in the conterminous U.S., we weighted the physical score twice as much as the water score to emphasize the size and condition of the units rather than hydrologic alteration. Note that because the final water score only represented units with some measured negative impact from hydrologic alteration, in the final resilience score integration, we only used the water score to reduce the physical score for units with *non-pristine hydrologic alteration scores*. Thus, for units with no measured hydrologic alteration, the final resilience score is simply the physical score. For the units with hydrologic alteration, the resilience score reflects the following formula: (2x Physical Score + 1x Water Score) / 3 if the result was less than the unit's existing physical score. The water score was used in this way because having any type of measured flow alteration should not increase the resilience score of a unit. Figure 3-38 shows the final resilience score for each HUC-12 unit based on this approach and (Table 3-15) shows the distribution of the resilience scores by river and stream size class.

**Table 3-15. Distribution of freshwater resilience category by stream and river size class.**

| Resilience Score | Alaska Area (km2) | % Alaska Area | % Stream Miles | *Headwater streams* | *Creeks & Streams* | *Small Rivers* | *Medium Rivers* | *Mainstem Rivers* | *Large Rivers* | *Great Rivers* |
|---|---|---|---|---|---|---|---|---|---|---|
| Far Above Avg. | 874,481 | 57% | 59% | 58% | 59% | 64% | 70% | 66% | 51% | 2% |
| Above Avg. | 445,808 | 29% | 28% | 29% | 29% | 25% | 17% | 13% | 17% | 72% |
| Slightly Above Avg. | 62,964 | 4% | 4% | 4% | 4% | 4% | 5% | 12% | 14% | 17% |
| Average | 98,309 | 6% | 6% | 7% | 6% | 6% | 8% | 10% | 16% | 10% |
| Slightly Below Avg. | 34,924 | 2% | 2% | 2% | 2% | 1% | 1% | 0% | 3% | 0% |
| Below Avg. | 18,981 | 1% | 1% | 1% | 1% | 1% | 0% | 0% | 0% | 0% |
| Far Below Avg. | 1,056 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **Total** | **1,536,522** | **100%** | **100%** | ***100%*** | ***100%*** | ***100%*** | ***100%*** | ***100%*** | ***100%*** | ***100%*** |
| **Miles** | | | **573,155** | ***292,103*** | ***183,810*** | ***66,041*** | ***24,086*** | ***2,848*** | ***2,665*** | ***1,601*** |

**Figure 3-38. Final freshwater resilience score.**



CHAPTER

# Freshwater Resilient & Connected Network

4

In this section we identify a representative, resilient, and connected network - the Freshwater Resilient and Connected Network (FRCN) - that if conserved or restored could sustain freshwater biodiversity while facilitating the movement of species to adapt to a changing climate.

Our approach to identifying the network was to first identify a portfolio of freshwater sites that have been recognized for their aquatic biodiversity value and then overlay the portfolio on the freshwater resilience map to identify a network of sites that were both resilient and biodiverse. As in the conterminous U.S., we did not set an area goal for the network's spatial extent, but we were conscious of the United Nations Convention on Biological Diversity Kunming-Montreal Global Biodiversity Framework Target 3 (UNEP 2022) to "ensure and enable that by 2030 at least 30 per cent of terrestrial and inland water areas were conserved…especially areas of particular importance for biodiversity."

## Recognized Biodiversity Value

We obtained two statewide datasets to represent rivers, streams, and lakes that had been recognized for their freshwater biodiversity value: the Anadromous Waters Catalog (ADF&G Sport Fish RTS, 2024) and High Complexity Floodplains (Whited et al. 2012) which are described below. Until further inventory of rare and common freshwater species across the state is completed, these datasets provide an initial picture, accurate in what they represent, but are likely to underestimate the full suite of areas that could qualify for freshwater recognized biodiversity value.

## Anadromous Waters Catalog

The Alaskan Anadromous Waters Catalog (AWC) currently lists almost 20,000 streams, rivers, and lakes which are important for the spawning, rearing, or migration of anadromous fish (ADF&G Sport Fish RTS, 2024). It formed the basis of the Alaskan Crucial Habitat Assessment Tool for aquatic species of concern (CHAT 2014). Protection of these specified waterbodies is addressed by sections of the AS 16.05.871 statue, which requires persons or governmental agencies to submit plans and specifications to the Alaska Department of Fish and Game and receive written approval in the form of a Fish Habitat Permit prior to beginning any construction or activity that would affect the waterbody. New streams are being added to the AWC annually as additional inventory confirms their importance for anadromous fishes. Although the 2024 AWC is currently the best representation of important anadromous waters, it is based on comprehensive surveys of a subset of drainages and is believed to represent only a fraction of the waterbodies used by anadromous species. Until all habitats are inventoried, they will not be protected under Alaskan state law (ADF&G Sport Fish RTS, 2024).

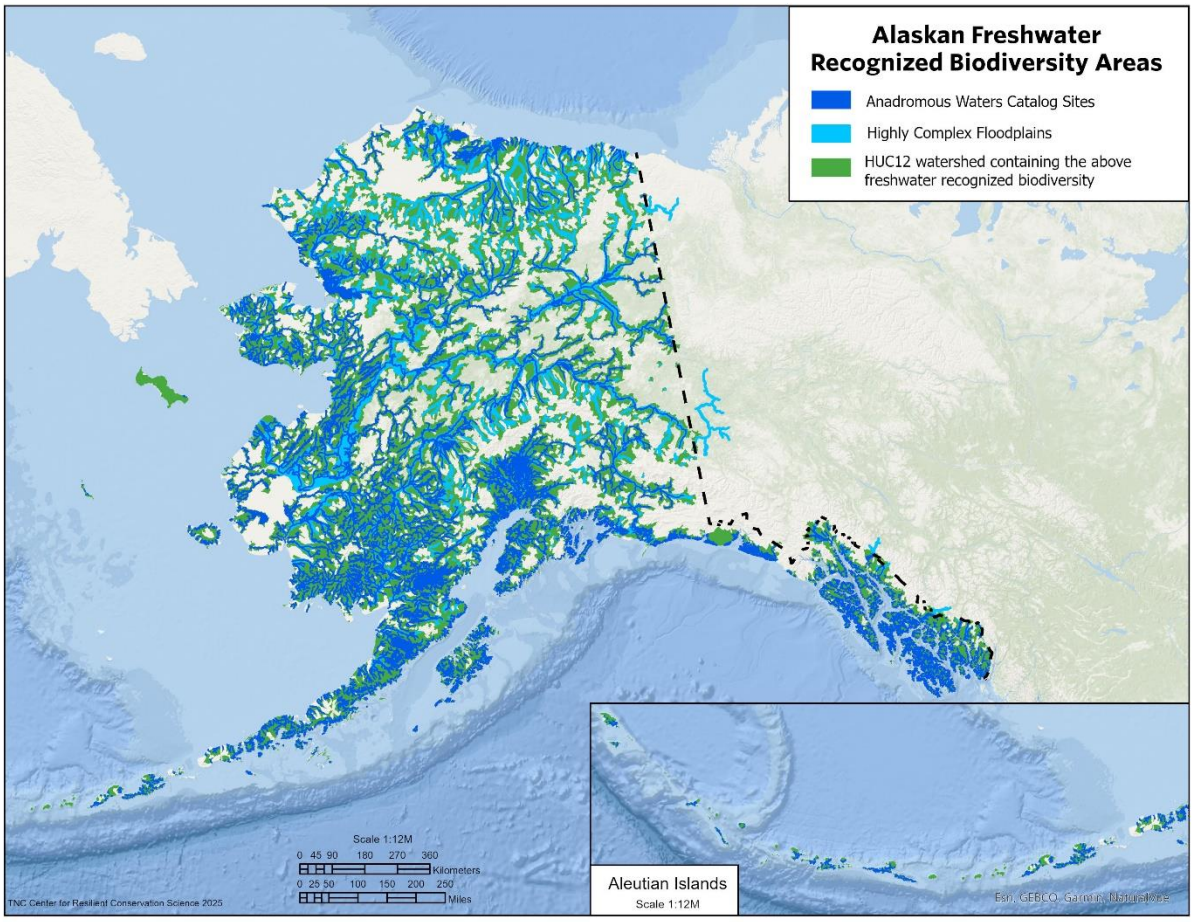
## High Complexity Floodplains

Floodplains support large and diverse populations of plants and animals and are critical areas where terrestrial and freshwater processes and species interact. Floodplains provide unique habitats which support natural flood storage and erosion control, facilitate groundwater recharge, water quality maintenance and are critical sources of energy and nutrients for organisms in adjacent and downstream riverine ecosystems. The value of floodplains to juvenile salmon production and sustainability has been repeatedly documented and successful juvenile salmon production has a strong relationship to the structure, organization, and hydrologic connections of the floodplain (i.e., "node-complexity," Whited et al. 2012). Floodplain node complexity has been comprehensively mapped for large floodplains across the entire state and was recommended as the most useful indicator of floodplain sections with high biological value (Whited et al. 2012 and pers comm. 2020). We adopted the scoring and threshold approach for mapping floodplain node-complexity as an indicator of floodplain biodiversity value that we developed in a previous assessment of Alaska's terrestrial resilience (Anderson et al. 2021). Each mapped floodplain patch was scored for node-complexity and converted to a z-score. Floodplain patches scoring above-average (>0.5 SD) within each of the three major ecoregions were used to represent streams with recognized biodiversity value.

## HUC-12 Integration of Recognized Biodiversity

For each HUC-12, we tabulated the length of Anadromous Waters Catalog streams and the area of Anadromous Waters Catalog lakes and High Complexity Floodplains. After visual inspection, we coded a HUC-12 as containing recognized freshwater biodiversity if it contained more than 0.25 km of streams or more than one acre of lake or floodplain. These thresholds were necessary to reduce error given the spatial precision of the input data. Overall, 60% of the HUC-12 watersheds (n=8,564) were flagged for biodiversity value, comprising 63% of the analyzed land area (Figure 4.1).

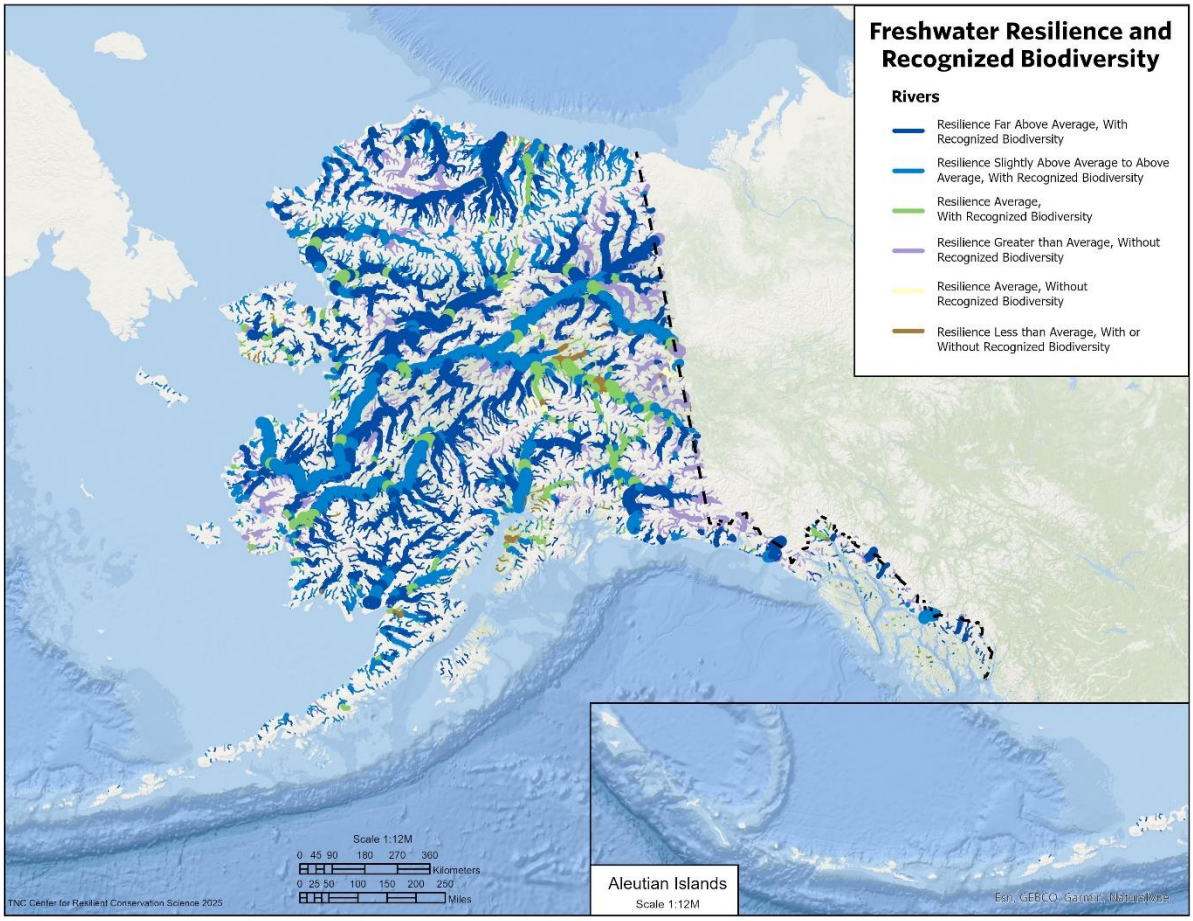
**Figure 4-1. Areas of freshwater recognized biodiversity value.** In aggregate, the freshwater biodiversity areas represent 63% of the land area of Alaska.




# A Freshwater Resilient and Connected Network (FRCN)

The Convention on Biological Diversity Target 3 calls for conservation of 30% of inland waters by 2030 (CBD 2022), but to date, most area-based conservation plans are strongly focused on land and are unlikely to sustain freshwater biodiversity on their own (The Nature Conservancy et al. 2022; Perry et al. 2024). We used the combined freshwater resilience and recognized biodiversity information to identify a set of sites that met goals for ecological representation, resilience, and biodiversity. We did not set a specific numeric goal for spatial extent (e.g. 30%) for Alaska but instead identified a network that met criteria for resilience and biodiversity and had good representation across ecological gradients and ecoregions (Figure 4-2). Our methods followed those we developed for the conterminous U.S. (Anderson et al. 2024).

**Figure 4-2. Rivers by freshwater resilience and recognized biodiversity.** This map shows rivers that are both resilient and have recognized biodiversity in blues. Those with average resilience and recognized biodiversity are green. Those that are resilient and do not have recognized biodiversity are purple. Rivers with average resilience and no recognized biodiversity are yellow, while any river scoring less than average for resilience is shown in brown regardless of its biodiversity value.




We began by identifying those HUC-12s that were both above-average for resilience (>0.5 SD) and contained recognized biodiversity value (Figure 4.2, Table 4.1). This combination covered 55% of Alaska and 57% of all stream and river miles. It included over 80% of large rivers, 61% of small rivers, and over 50% of all stream lengths. In contrast, this category covered only 18% of the analysis area in the conterminous U.S.

Next, we identified HUC-12s with recognized biodiversity but only average resilience to hone-in on important areas with "restorable" resilience. This set made up only 5% of all streams and rivers in the state but including them in the network adds some critical connectivity segments within larger network. We assessed the restorability of each unit in this set by examining their individual resilience components. If all individual factors scored average or better, we identified the unit as *Restorable*. If only one factor scored below-average and the rest were average or better, we identified the strategy needed to increase resilience: *Restore Condition* = below-average condition, *Restore Flow* = below-average hydrologic

alteration, *Reconnect* = below average size and presence of a dam (Figure 4.3). Because the integrity of Alaskan streams is so high and their fragmentation is so low, the restorable category may represent sites with only relatively minor impacts from very small amounts of impervious surfaces and development. Adding the restorable HUC-12s to the previous set brings the total Freshwater Resilient and Connected Network to 60% of the area of Alaska and 62% of all streams and rivers (Figure 4.3, Table 4-2. ).

**Table 4-1. Distribution of freshwater features by resilience and biodiversity class (AA = Above Average and BA = Below Average)**

| Resilience Score | Total Area ($km^2$) | % Area | % Stream Length | *Headwater Streams* | *Creeks & Streams* | *Small Rivers* | *Medium Rivers* | *Mainstem Rivers* | *Large Rivers* | *Great Rivers* |
|---|---|---|---|---|---|---|---|---|---|---|
| **With Biodiversity** | | | | | | | | | | |
| Far-Above Avg. | 502,783 | 33% | 35% | 34% | 32% | 40% | 62% | 65% | 51% | 1% |
| Above Avg. | 293,621 | 19% | 18% | 19% | 17% | 18% | 15% | 12% | 17% | 71% |
| Slightly AA. | 50,476 | 3% | 3% | 3% | 3% | 3% | 5% | 12% | 14% | 17% |
| Average | 74,272 | 5% | 5% | 5% | 4% | 4% | 7% | 9% | 16% | 10% |
| **FRCN total** | **921,153** | **60%** | **62%** | **61%** | **57%** | **66%** | **89%** | **99%** | **97%** | **99%** |
| Slightly BA. | 31,523 | 2% | 2% | 2% | 1% | 1% | 1% | 0% | 3% | 0% |
| Below Avg. | 16,501 | 1% | 1% | 1% | 1% | 1% | 0% | 0% | 0% | 0% |
| Far Below Avg. | 939 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **Without Biodiversity** | | | | | | | | | | |
| Far-Above Avg. | 371,698 | 24% | 24% | 24% | 27% | 23% | 8% | 0% | 0% | 0% |
| Above Avg. | 152,187 | 10% | 9% | 10% | 11% | 7% | 1% | 1% | 0% | 1% |
| Slightly AA. | 12,487 | 1% | 1% | 1% | 1% | 1% | 0% | 0% | 0% | 0% |
| Average | 24,037 | 2% | 1% | 2% | 2% | 1% | 1% | 1% | 0% | 0% |
| Slightly BA. | 3,401 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Below Avg. | 2,479 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Far Below Avg. | 117 | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **Total** | **1,536,522** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** |

**Figure 4-3. The Freshwater Resilient and Connected Network (FRCN).** The networks shown in the map cover 62% of all stream and river miles in Alaska.

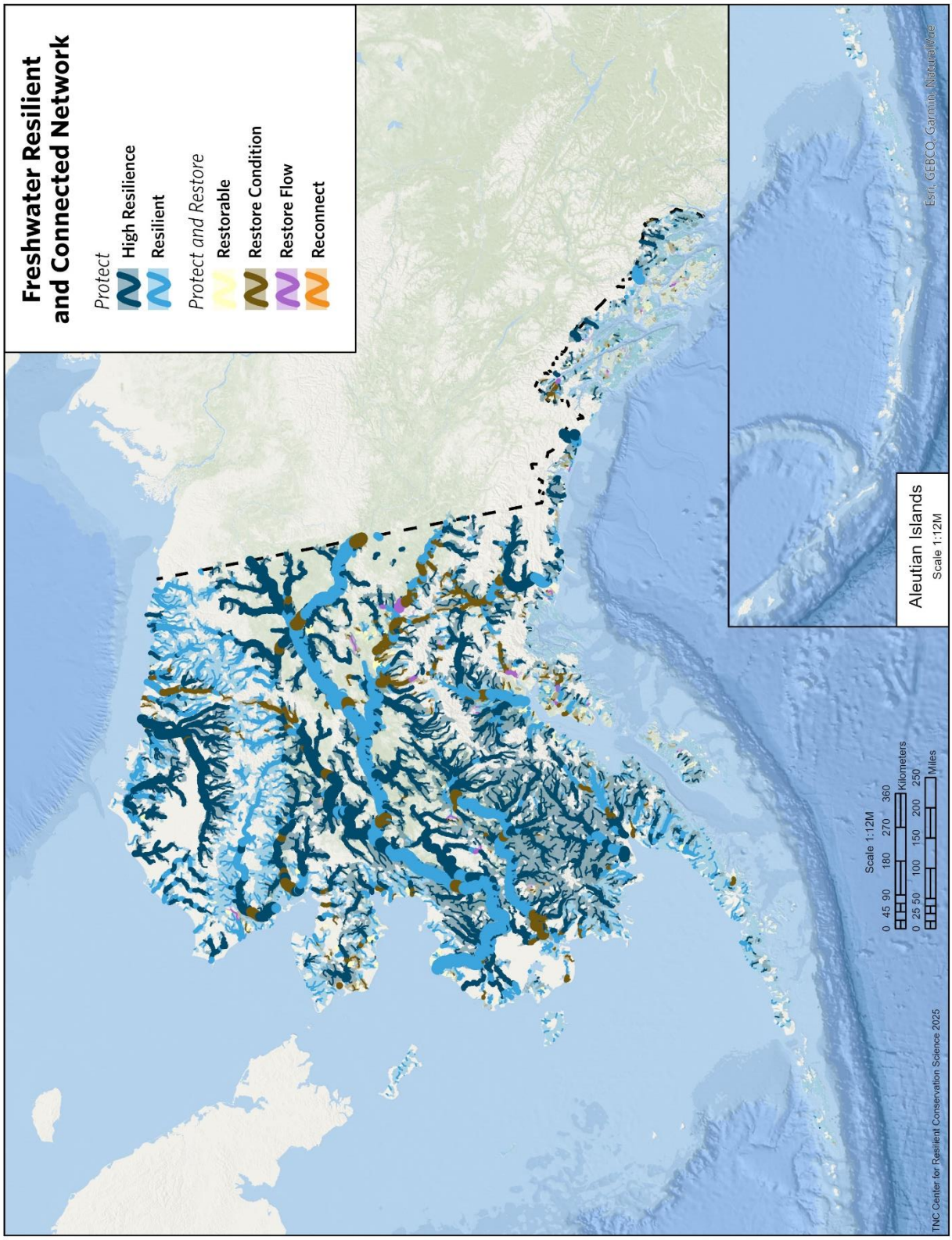


**Table 4-2. Length of streams and rivers in the Freshwater Resilient and Connected Network.**

| Freshwater Resilient & Connected Network | Total Length | *Headwater Streams* | *Creek Streams* | *Small Rivers* | *Medium Rivers* | *Mainstem Rivers* | *Large Rivers* | *Great Rivers* |
|---|---|---|---|---|---|---|---|---|
| **Resilience Score** | | | | **Miles** | | | | |
| Far Above Average | 201,131 | 98,102 | 58,492 | 26,510 | 14,811 | 1,854 | 1,338 | 24 |
| Above Average | 103,994 | 54,590 | 32,021 | 11,784 | 3,674 | 341 | 439 | 1,144 |
| Slightly Above Average | 19,038 | 9,555 | 5,295 | 2,109 | 1,104 | 341 | 366 | 267 |
| Average: Restorable | 5,872 | 3,389 | 1,915 | 389 | 133 | 27 | 18 | 0 |
| Average: Restore Condition | 20,791 | 10,454 | 5,859 | 2,234 | 1,472 | 234 | 385 | 153 |
| Average: Restore Flow | 395 | 204 | 134 | 57 | 0 | 0 | 0 | 0 |
| Average: Restore Flow and Condition | 1,351 | 686 | 337 | 195 | 109 | 0 | 24 | 0 |
| Average: Reconnect | 13 | 6 | 8 | 0 | 0 | 0 | 0 | 0 |
| **Total FRCN** | **352,584** | **176,987** | **104,061** | **43,279** | **21,302** | **2,797** | **2,570** | **1,588** |
| Not in FRCN | 213,062 | 111,298 | 77,237 | 21,867 | 2,550 | 41 | 70 | 0 |
| **Grand Total** | **565,646** | **288,285** | **181,299** | **65,146** | **23,852** | **2,837** | **2,640** | **1,588** |
| **Resilience Score** | | | | **Percent** | | | | |
| Far Above Average | 36% | 34% | 32% | 41% | 62% | 65% | 51% | 2% |
| Above Average | 18% | 19% | 18% | 18% | 15% | 12% | 17% | 72% |
| Slightly Above Average | 3% | 3% | 3% | 3% | 5% | 12% | 14% | 17% |
| Average: Restorable | 1% | 1% | 1% | 1% | 1% | 1% | 1% | 0% |
| Average: Restore Condition | 4% | 4% | 3% | 3% | 6% | 8% | 15% | 10% |
| Average: Restore Flow | 0% | 0% | 0% | 0% | 0% | 0% | 1% | 0% |
| Average: Restore Flow and Condition | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Average: Reconnect | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **Total FRCN** | **62%** | **61%** | **57%** | **66%** | **89%** | **99%** | **97%** | **100%** |
| Not in FRCN | 38% | 39% | 43% | 34% | 11% | 1% | 3% | 0% |
| **Grand Total** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** |

# Representation of Freshwater Features in the Freshwater Resilient and Connected Network

## *Representation of Freshwater Features*

To measure how well the Freshwater Resilient and Connected Network (FRCN) represents the full diversity of freshwater species and ecosystems, we overlaid a series of individual datasets on it and assessed how well the features represented were captured by the network. These included:

- Stream and river size classes
- Ecoregions: freshwater and terrestrial
- Wetlands, lakes, and ponds
- Aquatic biodiversity
- Free-flowing rivers

### Stream Size

An overlay of all stream miles revealed that the FRCN contains 63% (353,000 miles) of streams and rivers in roughly the same size class proportion that they occur on the landscape (Table 4-3). The only discrepancies were in the medium-mainstem rivers, which together represent 5% of Alaska's rivers, but 7% of the FRCN. The difference is made up in the headwater and creeks size class which represents 83% of Alaska but 80% of the FRCN.

**Table 4-3. Stream size classes in the FRCN.**

| Stream Size Class | % FRCN | FRCN Miles | % Alaska | Alaska Miles |
|---|---|---|---|---|
| Headwater & Creeks | 80% | 281,048 | 83% | 469,584 |
| Small Rivers | 12% | 43,279 | 12% | 65,146 |
| Medium-Mainstem Rivers | 7% | 24,098 | 5% | 26,689 |
| Large to Great Rivers | 1% | 4,158 | 1% | 4,228 |
| **Total** | 100% | 352,584 | 100% | 565,646 |

## *Ecoregions*

The network represents at least 40% of the Alaskan stream miles in each HUC4 watershed (avg. 57%, range 27%-78%) except for the Upper Yukon, which is mostly in Canada (27%,Table 4-4). At a larger scale, the three overarching freshwater regions also had over 40% of their streams and rivers included, with 40% in the Upper Yukon, 49% in Alaska and Canada Pacific Coastal, and 64% in the Alaskan Coastal freshwater ecoregion. This suggests that the FRCN is a very well distributed network of resilience and biodiversity.

**Table 4-4. Distribution of freshwater resilience classes by recognized biodiversity value and freshwater ecoregion.**

| | Freshwater Ecoregion | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Alaska & Canada Pacific Coastal | | | Alaskan Coastal | | | | | Upper Yukon | | | |
| **Resilience Score** | **South Central Alaska** | **Southeast Alaska** | **Total** | **Arctic Alaska** | **Lower Yukon River** | **Northwest Alaska** | **Southwest Alaska** | **Total** | **Middle Yukon River** | **Upper Yukon River** | **Total** | **Alaska Total** |
| **With Biodiversity** | | | | | | | | | | | | |
| Far Above Avg. | 30% | 21% | 27% | 28% | 47% | 26% | 53% | 40% | 29% | 16% | 28% | 35% |
| Above Avg. | 15% | 20% | 17% | 28% | 11% | 35% | 18% | 22% | 9% | 8% | 9% | 18% |
| Slightly Above Avg. | 6% | 3% | 5% | 3% | 2% | 2% | 4% | 3% | 3% | 0% | 3% | 3% |
| **Subtotal** | 51% | 44% | 49% | 58% | 60% | 64% | 75% | 65% | 42% | 24% | 40% | 57% |
| Average | 10% | 7% | 9% | 3% | 4% | 5% | 3% | 3% | 7% | 3% | 6% | 5% |
| **FRCN total** | **61%** | **50%** | **58%** | **61%** | **63%** | **69%** | **78%** | **68%** | **49%** | **27%** | **46%** | **62%** |
| Slightly Below Avg. | 2% | 5% | 3% | 1% | 0% | 3% | 1% | 1% | 1% | 0% | 1% | 2% |
| Below Avg. | 2% | 5% | 3% | 0% | 0% | 0% | 0% | 0% | 1% | 0% | 0% | 1% |
| Far Below Avg. | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **Without Biodiversity** | | | | | | | | | | | | |
| Far Above Avg. | 29% | 29% | 29% | 15% | 27% | 10% | 12% | 16% | 39% | 60% | 42% | 24% |
| Above Avg. | 4% | 10% | 6% | 19% | 7% | 17% | 8% | 12% | 5% | 4% | 5% | 9% |
| Slightly Above Avg. | 1% | 0% | 1% | 2% | 0% | 1% | 0% | 1% | 1% | 1% | 1% | 1% |
| Average | 1% | 0% | 1% | 1% | 1% | 1% | 1% | 1% | 3% | 6% | 4% | 1% |
| Slightly Below Avg. | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 1% | 0% | 0% |
| Below Avg. | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 1% | 0% | 0% |
| Far Below Avg. | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **Grand Total** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** |

Representation was even more comprehensive when measured against the terrestrial ecoregions with all ecoregions having over 40% of their streams and rivers in the FRCN and averaging 64% per ecoregion (range 41%-86%). Eight of the eleven ecoregions had over 50% of their freshwater network included in the resilient and biodiverse FRCN categories (Table 4-5). These were the most resilient systems in terms of connectivity, condition, intact water regime, and they contained areas recognized as important for freshwater biodiversity.

**Table 4-5. Distribution of freshwater resilience classes by recognized biodiversity value and terrestrial ecoregion.**

| | Terrestrial Ecoregion | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Resiliene Score** | **Alaska Peninsula** | **Alaska Range** | **Alaska-Yukon Arctic** | **Bering Sea And Aleutian Islands** | **Beringian Tundra** | **Bristol Bay Basin** | **Cook Inlet Basin** | **Gulf Of Alaska Mountains and Fjordlands** | **Interior Alaska Taiga** | **S.E. Alaska - B.C. Coastal Forest and Mountains** | **Yukon Plateau and Flats** | **Alaska Total** |
| **With Biodiversity** | | | | | | | | | | | | |
| Far Above Avg. | 25% | 37% | 20% | 0% | 36% | 57% | 33% | 22% | 58% | 19% | 29% | 35% |
| Above Avg. | 52% | 4% | 35% | 54% | 21% | 22% | 17% | 13% | 6% | 27% | 6% | 18% |
| Slightly Above Avg. | 7% | 5% | 3% | 1% | 3% | 4% | 14% | 2% | 3% | 4% | 2% | 3% |
| | 83% | 46% | 58% | 55% | 60% | 83% | 64% | 38% | 67% | 50% | 37% | 57% |
| Average | 2% | 9% | 3% | 1% | 6% | 3% | 18% | 6% | 5% | 8% | 4% | 5% |
| **FRCN total** | **86%** | **54%** | **61%** | **55%** | **66%** | **86%** | **82%** | **44%** | **72%** | **58%** | **41%** | **62%** |
| Slightly Below Avg. | 1% | 0% | 1% | 33% | 1% | 1% | 6% | 2% | 1% | 8% | 1% | 2% |
| Below Avg. | 0% | 0% | 0% | 0% | 0% | 0% | 7% | 2% | 0% | 9% | 0% | 1% |
| Far Below Avg. | 0% | 0% | 0% | 0% | 0% | 0% | 2% | 0% | 0% | 0% | 0% | 0% |
| **Without Biodiversity** | | | | | | | | | | | | |
| Far Above Avg. | 2% | 39% | 11% | 1% | 14% | 6% | 1% | 43% | 25% | 18% | 49% | 24% |
| Above Avg. | 11% | 2% | 24% | 9% | 17% | 6% | 0% | 8% | 1% | 6% | 3% | 9% |
| Slightly Above Avg. | 0% | 1% | 2% | 0% | 0% | 0% | 0% | 1% | 0% | 0% | 1% | 1% |
| Average | 0% | 3% | 1% | 0% | 1% | 1% | 0% | 1% | 1% | 0% | 4% | 1% |
| Slightly Below Avg. | 0% | 0% | 0% | 1% | 0% | 0% | 0% | 0% | 0% | 0% | 1% | 0% |
| Below Avg. | 0% | 0% | 0% | 0% | 0% | 0% | 1% | 0% | 0% | 0% | 1% | 0% |
| Far Below Avg. | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **Grand Total** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** |

## *Aquatic Biodiversity*

To evaluate the representation of recognized biodiversity features, we overlaid the FRCN on the individual source datasets: Anadromous Waters Catalog (AWC) and Complex Floodplains. Results indicate the FRCN includes 93% of AWC stream and river lengths, 99% of AWC lakes/ponds, and 97% of the most complex floodplain areas (Table 4-6). The most resilient category in the FRCN, Far Above Average, includes over half of the AWC streams and rivers and complex floodplains in the state. The biodiversity features not included in the FRCN occur primarily along the coast where development and barriers are concentrated.

**Table 4-6. Representation of recognized biodiversity source data.** Percent values represent the percentage of the total length area of the given type of recognized biodiversity that falls within a given FRCN category.

| **Biodiversity Representation** | **AWC Streams & Rivers** | **AWC lakes & ponds** | **Complex Floodplains** |
|---|---|---|---|
| FRCN Category | miles | acres | acres |
| Far Above Average | 51% | 27% | 54% |
| Above Average | 27% | 43% | 25% |
| Slightly Above Average | 6% | 26% | 9% |
| Average: Restorable | 2% | 1% | 1% |
| Average: Restore Condition | 7% | 3% | 7% |
| Average: Restore Flow and Condition | 1% | 0% | 0% |
| Average: Restore Flow | 0% | 0% | 0% |
| Average: Restore Size | 0% | 0% | 0% |
| **Total in the FRCN** | **93%** | **99%** | **97%** |
| **Not in the FRCN** | 7% | 1% | 3% |
| Total % | 100% | 100% | 100% |
| **Total Miles or Acres** | **78,936** | **3,195,581** | **18,102,614** |

## Free-flowing Rivers

Over 90% of all Alaskan rivers are open to the ocean and mostly free flowing. River dams are predominantly located in the headwaters or upper reaches of the Yukon River in Canada or on the Tanana River in the U.S., fragmenting only a small portion of these gigantic river networks (Figure 4-4). River networks entirely without any dams or barriers are located near the coast and ring the entire state (Figure 4.4).

The FRCN rivers are almost entirely (98%) open to the ocean with only one small segment of the Chena River above the Moose Creek Dam where the Mullen Slough and Lohi Creek small rivers are disconnected from the ocean (Figure 4.5). This FCN is of average size (3,745 sq.km) and its HUC12 watersheds score high for condition and flow. The 114 miles of its river network are included in the FRCN as slightly-above-average or average (restorable) resilience.

**Figure 4-4. River connectivity.**

River networks in grey have no internal barriers and are entirely free flowing to the ocean. The gigantic river networks in blue are connected to the ocean but have one to three internal dams on their upper river reaches. The red areas show the size of the disconnected networks.

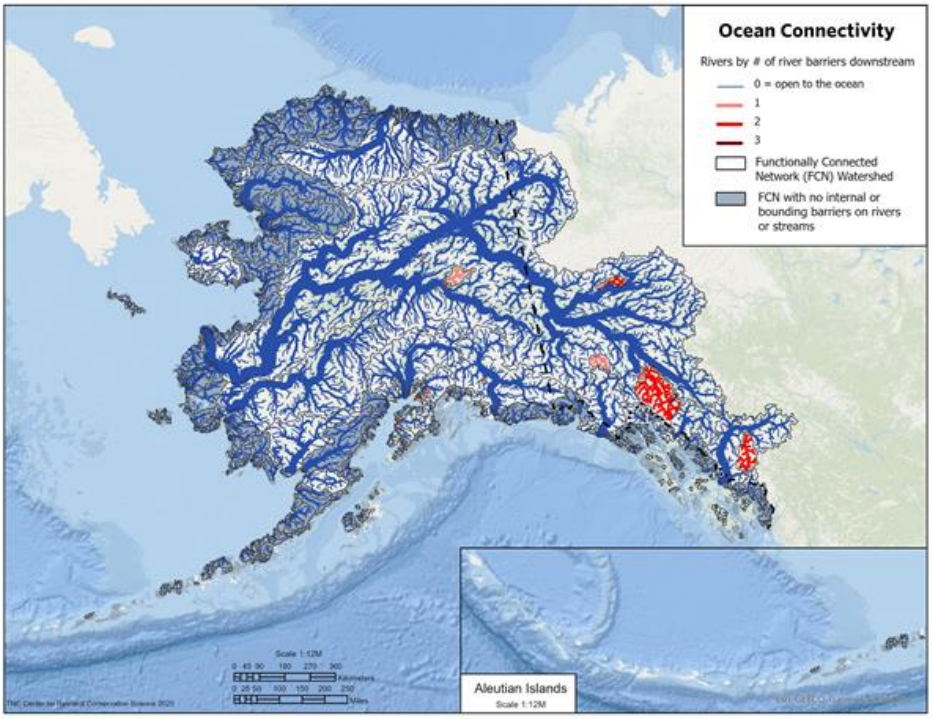
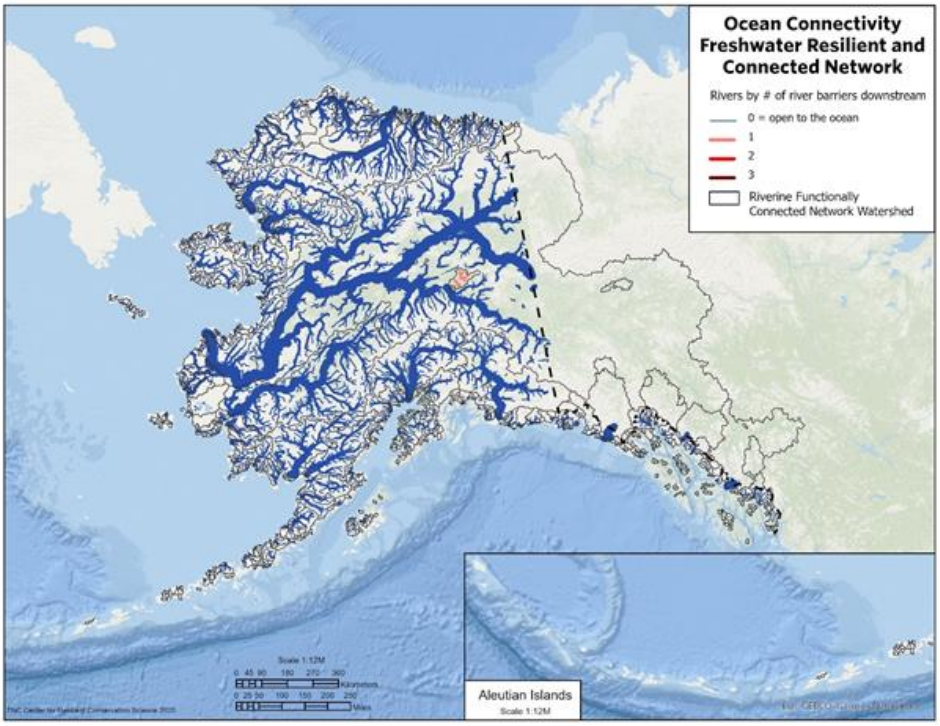



**Figure 4-5. FRCN connectivity.** Over 98% of FRCN rivers are connected to the ocean with only a small area on the Chena River (red) being cut off.



## Wetlands, Floodplains, Lakes, and Ponds

To evaluate the representation of wetlands, we overlaid the FRCN on a wetland dataset compiled for our terrestrial resilience analysis (Anderson et al. 2021) as well as on the river floodplains used in that terrestrial analysis and the condition section of this freshwater resilience assessment (Whited 2012, TNC Active River Areas for rivers 2021). As part of the terrestrial resilience analysis, we developed a terrestrial Resilient and Connected Network (TRCN) designed to sustain biodiversity, connectivity, and climate resilience for all of Alaska. The dataset included millions of acres of wetlands and floodplains assessed for their terrestrial resilience factors of microclimatic buffering, wetland density, and local connectedness. Non-wetland floodplain refers to areas mapped as floodplain, but that do not maintain permanent water or wetlands. Many floodplains have both wet and dry regions.

Results indicate that 69% of all mapped wetlands are in the FRCN and another 26% are in the terrestrial RCN. Similarly, 84% of the floodplain uplands are in the FRCN with another 9% in the terrestrial RCN. Together, 95% of the wetlands and 93% of the floodplain uplands are captured by the two networks. Visual comparison highlights how the terrestrial RCN captures more isolated basin wetlands and large peatlands while the FRCN is focused on riverine and floodplain wetlands (Figure 4-6, Table 4-7).

**Figure 4-6. Overlay of wetlands and floodplains on the freshwater and terrestrial RCNs.**

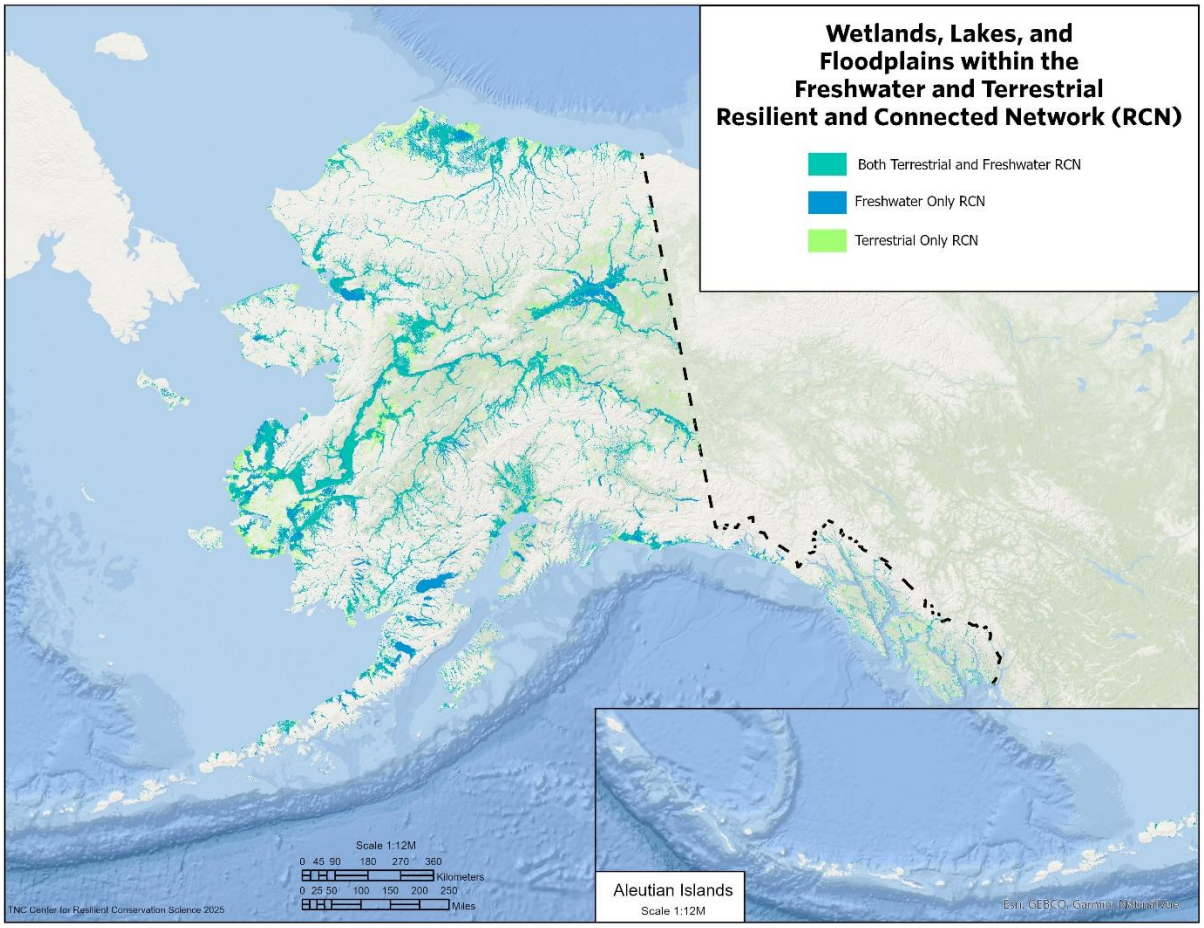


**Table 4-7. Overlay of wetlands and river floodplains on the freshwater and terrestrial RCNs.**

| Feature | Resilient and Connected Networks (RCN) | | | | |
|---|---|---|---|---|---|
| | Acres | | | | |
| | Freshwater | Both | Terrestrial | Not RCN | Total |
| **Wetlands** | **2,484,448** | **16,946,823** | **7,373,574** | **1,607,884** | **28,412,730** |
| Basin | 1,685,927 | 8,591,094 | 5,353,494 | 1,189,564 | 16,820,080 |
| Floodplain | 798,521 | 8,355,729 | 2,020,080 | 418,320 | 11,592,650 |
| **Upland** | **86,737,034** | **108,690,778** | **63,361,134** | **74,610,908** | **333,399,854** |
| Floodplain | 8,088,361 | 14,722,669 | 2,363,462 | 1,960,808 | 27,135,300 |
| **Total** | 101,232,875 | 125,637,601 | 67,399,005 | 80,365,382 | 374,634,864 |
| | Percent | | | | |
| | Freshwater | Both | Terrestrial | Not RCN | Total |
| **Wetlands** | **9%** | **60%** | **26%** | **6%** | **100%** |
| Basin | 10% | 51% | 32% | 7% | 100% |
| Floodplain | 7% | 72% | 17% | 4% | 100% |
| **Upland** | **26%** | **33%** | **19%** | **22%** | **100%** |
| Floodplain | 30% | 54% | 9% | 7% | 100% |
| **Total** | 27% | 34% | 18% | 21% | 100% |

Lakes and ponds are also well represented in the FRCN with 74% of floodplain lakes and 59% of basin lakes represented in the network. This amounts to 68% of all lake and pond area, which is slightly higher than the 60% area of the network (Table 4-8).

**Table 4-8. Lakes and ponds in the freshwater RCN.**

| Lake and Ponds | FRCN | | Not in FRCN | | |
|---|---|---|---|---|---|
| | Acres | % | Acres | % | Total |
| **Lakes and Ponds** | **8,675,690** | **68%** | **4,146,591** | **32%** | **12,822,281** |
| Basin | 3,418,353 | 59% | 2,328,834 | 41% | 5,747,186 |
| Floodplain | 5,257,337 | 74% | 1,817,757 | 26% | 7,075,094 |

## Summary of Representation in the Alaska FRCN

**VERY GOOD** (over 66% representation)

- **Stream Size Classes:** Representation is very close to natural proportions.
- **Free-Flowing Rivers:** Over 90% of all completely free-flowing rivers and 98% of all rivers open to the ocean are in the FRCN.
- **Recognized Biodiversity Value:** Over 93% of reaches recognized for their biodiversity value are in the FRCN.
- **Ecoregions:** 91% of freshwater ecoregions have over 30% of their perennial streams, and 100% of terrestrial ecoregions have over 30% of their area in the FRCN.
- **Floodplain Wetlands:** 79% of all floodplain wetlands are in the FRCN. An additional 17% are in the terrestrial RCN.
- **Lakes and Ponds:** 68% of all lakes and ponds are in the FRCN.

**GOOD** (33%-66% representation)

- **Basin Wetlands:** 61% of all basin wetlands are in the FRCN. An additional 32% are in the terrestrial RCN.

CHAPTER

# Freshwater Conservation Status

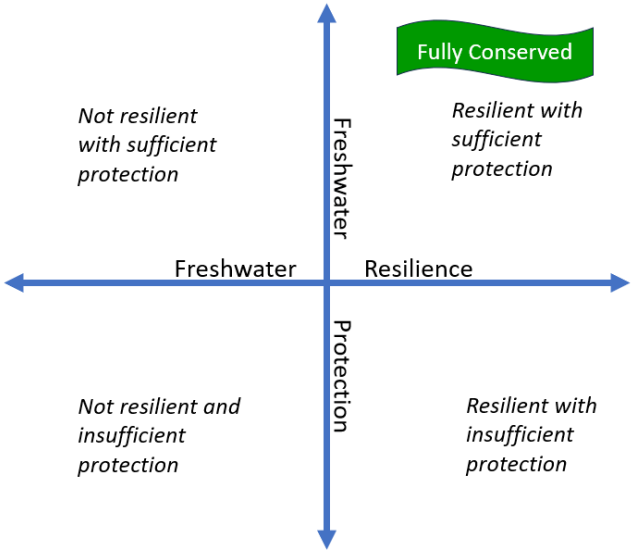
5

## General Model for Conservation Status of Freshwater Networks

Conservation of the environment may require both protection, which is the prevention of future degradation (Higgins et al. 2021), and restoration of ecologic function when a system is below a level of viability (Possingham et al. 2015). Ideally then, to say that an instance of an ecosystem is *conserved*, it would be above a threshold for ecologic condition based on sufficient function and long term viability, and it would be protected, based on sufficient legal mechanisms or community management agreements that prevent further degradation (Higgins et al. 2021). It can be difficult to establish these thresholds. In practice, conservationists prefer to set goals for improving specific dimensions of ecosystems, and tend to measure actions taken rather than ecological outcomes, which may take years to appear and are difficult to detect (Stephenson 2019). Yet area-based goals for protecting land, oceans, and inland waters, such as the CBD 30x30 initiative, require that we have a means to estimate whether something is conserved or not.

Our definition of "conserved," establishes two axes to assess conservation (Figure 5-1). The first axis is the level of freshwater resilience of a given river reach. As we described in Chapter 3, freshwater resilience encompasses both condition and viability by evaluating the key ecological attributes of rivers from the perspective of what will contribute to the climate resilience of that river into the future. The resilience score can thus serve as an estimate of a reach's resilience. The second axis is the level of protection. Here we determine this by combining the local protection score from American Rivers Protected Rivers Index (PRI, CSP 2025) with our own analysis of an upstream conservation land index to protect regulating function for hydrologic regime and water quality as described below.

**Figure 5-1. Conservation status is defined by two axes, resilience and protection.**




# Protection Class

We define protection as the establishment and implementation of mechanisms that avoid future impacts to freshwater ecosystems for 25 years or more, or have high probability of renewal and enforceability, or have completely alleviated the potential for a future threat (Higgins et al. 2021). Each mechanism is measured with respect to an ecosystem's Key Ecological Attributes (KEAs) that include habitat, water quality, hydrologic regime, connectivity, and biotic composition (Higgins et al. 2021).

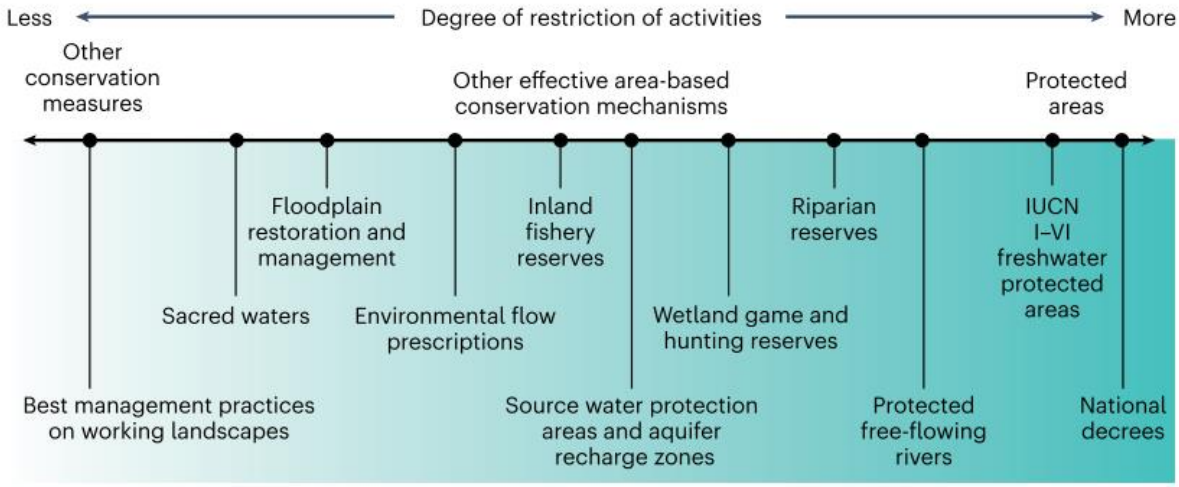
The United States has a web of federal laws such as the Clean Water Act that are intended to protect rivers everywhere, and one might suppose that they are. But that is not the case given the law's attempt to balance interests, variable implementation by states, and the impact of judicial interpretation of the law. For example, in May 2025, the Supreme Court's Sackett decision removed almost fifty years of federal protection for wetlands unless they meet a narrow, and not scientifically supported definition, in which only wetlands with a surface connection are important to the health of the nation's waterbodies (McElfish 2023).

Protection mechanisms exist at all levels of governance (Figure 5-2, Flitcroft et al. 2023), but there are limits to our ability to translate policy to specific locations. As with the freshwater resilience score, our findings are a starting place to identify where and what types of conservation actions are needed to achieve protection, but application of local information is absolutely warranted before specific conservation actions are taken.

Given that context, the American Rivers Protected Rivers Index (PRI, CSP 2025) is an ambitious attempt to connect measures of local protection to each KEA. After studying it extensively, we adopted it in its entirety as an estimate of each stream reach's local protection. To completely assess protection, however, we combined the local protection level with a

measure of regulating function based on the amount of conservation land in the contributing area.

**Figure 5-2. Freshwater protections fall along a spectrum of management intensity and restriction (Flitcroft et al. 2023).**




# Local Protection

The American Rivers Protected River Index (PRI) includes five categories of protection, most of which have multiple specific mechanisms. These categories are:

<u>River Conservation</u>
: includes Outstanding National Resource Waters, Outstanding Tribal Resource Waters, or equivalent state water quality protection designations, national Wild and Scenic River System designations, and state wild and scenic rivers.

<u>Riparian and Floodplain Conservation Mechanisms</u>
: includes riparian buffers; watershed protection areas; riparian, floodplain, and wetland conservation areas; and fishing management areas.

<u>Endangered Species Critical Habitat</u>

<u>Terrestrial Protected Areas</u>
: two subclasses – strict and other.

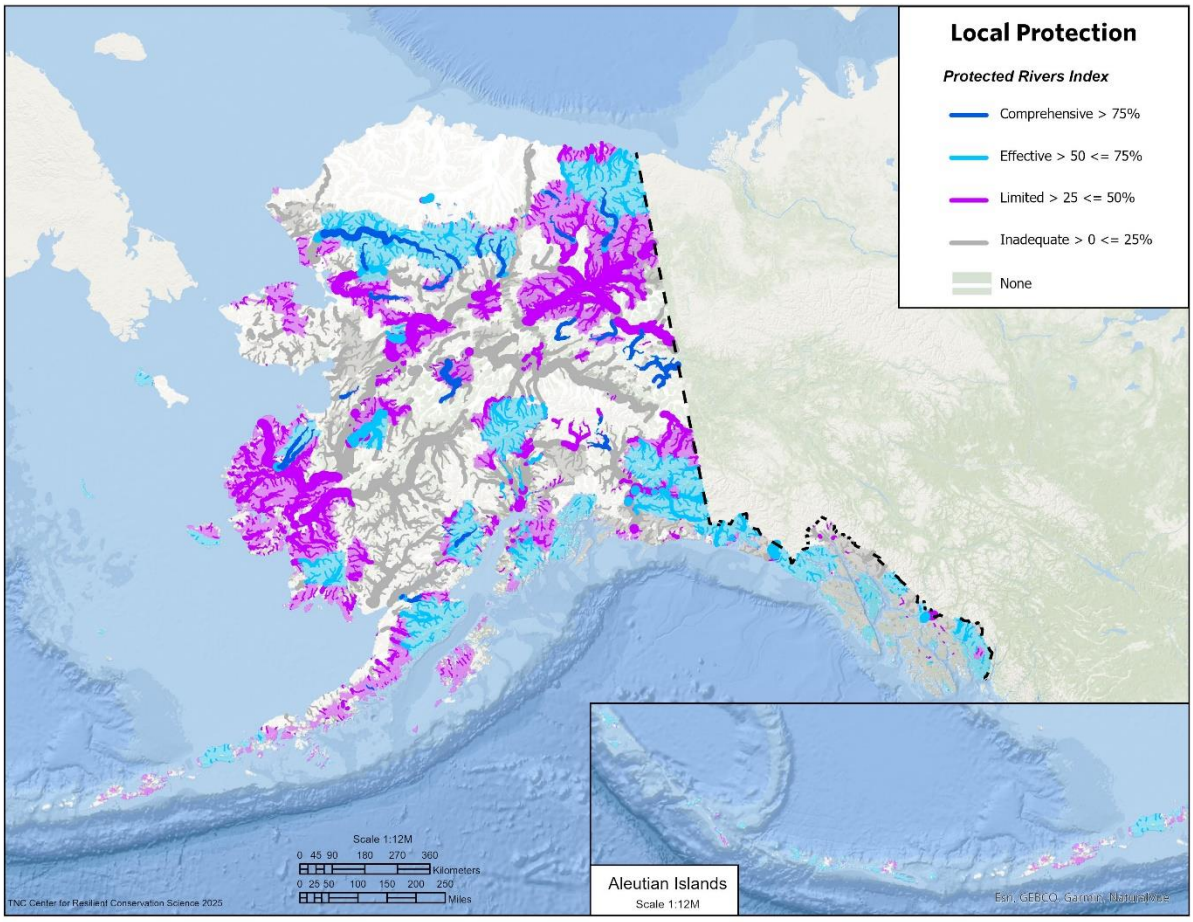
<u>Multiple Land Use</u>
: distinguished for special management purposes.

The PRI was calculated by "attributing different weights to each protection mechanism according to their potential conservation effectiveness and accounting for the protection of surrounding lands beyond the river channel" (CSP 2025). The weights were determined from how fully each mechanism potentially protects each key ecological attribute of freshwater ecosystems (sensu Higgins et al. 2021). Weights were assigned values between 0 and 1 for each of the five KEAs of hydrologic regime, connectivity, water quality, habitat, and biotic

composition for the protection mechanisms. American Rivers graciously made their results available to us as NHD High resolution arc data (Comte, L. 2025).

To integrate the PRI into our protection class, we calculated the PRI for the entire length of each NHD reach by summing the five individual scores for each KEA: hydrologic regime, connectivity, water quality, habitat, and biotic composition (values range from 0 to 1 per KEA). We converted the values to percents by dividing the total score by five (the maximum score). To transfer these scores to our project hydrology, we rasterized the reach scores and assigned the nearest PRI score to each 90-m cell in our hydrography using a Euclidean allocation nibble function in GIS. We then summarized this raster dataset for each reach to calculate the mean PRI of each stream or river arc. Following American Rivers, we report the PRI in five classes where those with a score of zero were classified as "No protection" and the remaining four classes were divided into equal interval groups where each bin included a quarter of the maximum possible score (Figure 5-3, CSP 2025).

**Figure 5-3. American Rivers Protected Rivers Index (PRI) applied to project hydrography.**



# Protection of Freshwater Upstream Regulating Function

Maintaining freshwater in a natural state is arguably the most effective and long-lasting tool for conserving species and habitats. By regulating the use of land and water within a network of places, conservation can sustain species populations and prevent habitat degradation at larger scales. However, because freshwater networks are integrally linked to the surrounding landscape, protection provided by lands managed for conservation depends not just on lands immediately adjacent to freshwater ecosystems, but also the lands and land use in the whole contributing area of the network (Flitcroft et al. 2023). We accounted for the protective benefit of upstream conservation lands to freshwater networks using a method modified from Abell et al. (2017), who argued that the simple intersection of protected areas with rivers misses that fluvial systems are also shaped by the character and condition of their entire catchments. Thus, this complements the PRI assessment of the local protective benefit of conservation lands by considering the protection potential of conservation lands in a reach's upstream catchment. Conservation lands in the upstream catchment are critical for their regulation of many functions, especially water quality and flow regime.

Our integration of upstream conservation land protection involved three parts. First, we calculated the amount of conservation lands upstream of each reach using The Nature Conservancy's comprehensive secured lands dataset (Olivero & Clark 2024). Next, we estimated the relative protective benefit of each different category of conservation ownership for regulating function and determined which areas should count toward the score. Third, we translated the results into scores.

## *Definition and Categories of Conservation Land*

In this report, "conservation land" refers to land that is permanently secured against conversion to development. This definition was adopted by an international group of American and Canadian scientists to encompass a wide variety of public and private ownership and management types. It goes beyond the more restrictive IUCN definition of "protected areas" which refers to land with a government designation aimed at the conservation of nature. Our definition includes public land designated for conservation but also includes land with no formal designation if the intent of the landowner or easement holder (public, private, or NGO) is for permanent conservation, and if there is a measurable capacity to fulfill the intent. For example, a permanent conservation easement held by an established land trust qualifies as conservation land even though it is privately held and has no designation.

For Alaska, TNC's Secured Lands dataset (Olivero & Clark 2024) was developed as part of TNC's terrestrial resilience analysis (Anderson et al. 2021). The foundation of the dataset is public land information maintained by each state, supplemented by federal land information from PAD-US, and private conservation land information compiled by TNC and the National Conservation Easement Database. We assigned a GAP Status to each tract, populated other standard attribute fields, and quality-checked the dataset for consistency and discrepancies across states. Importantly, TNC's dataset is focused on permanent conservation and only includes land where the intent of the owner or easement holder is conservation in perpetuity and there is some legal capacity to fulfill that intent. Thus, places with important temporary,

volunteer, or one-time conservation activities are not included in the dataset. We distinguished six major types of land secured from conversion to development, from most protective to least: GAP 1, GAP 2, GAP 3 non-BLM land, GAP 3 BLM land, State Board Lands, and Permanent Agricultural Easements (Figure 5-4), the latter two were not present in Alaska.

**Figure 5-4. Conservation lands in Alaska by protection class.**

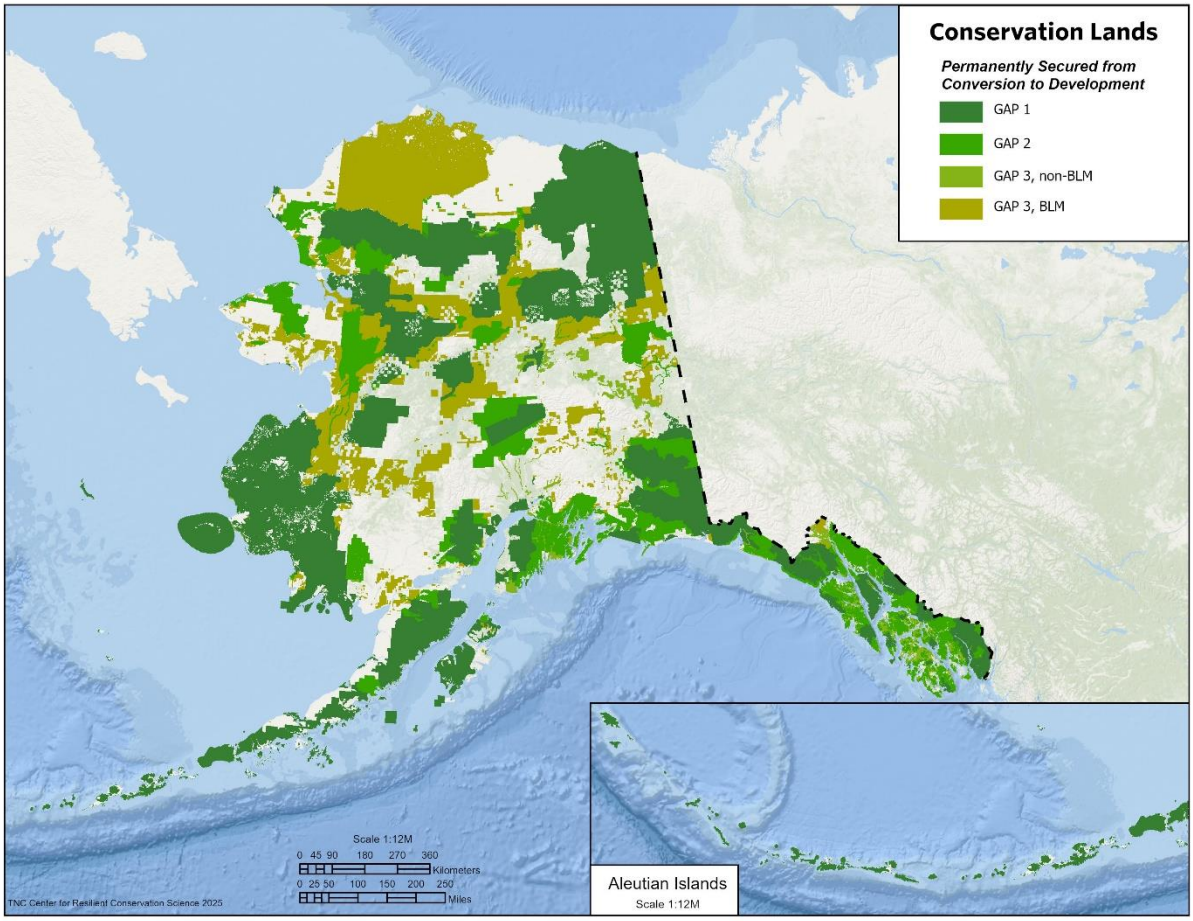


**Table 5-1. Conservation land categories used in this analysis.**

| Conservation Land Category | Definition | Additional Information |
|---|---|---|
| GAP 1 | Permanently Secured for Nature and Natural Processes. Managed for biodiversity with all natural processes, little to no human intervention. | Primary intention of the owner or easement holder is for biodiversity, nature protection, natural diversity, and natural processes. Land and water managed through natural processes including disturbances with little or no human intervention. Examples: wilderness area, some national parks. |
| GAP 2 | Permanently Secured for Nature with Management: Managed for biodiversity, with hands-on management or interventions. | Primary intention of the owner or easement holder is for biodiversity conservation, nature protection, and natural diversity. Land and water managed for natural biodiversity conservation, but which may include some hands-on manipulation or suppression of disturbance and natural processes. Examples: national wildlife refuges, areas of critical environmental concern, inventoried roadless areas, some natural areas and preserves. |
| GAP 3, non-BLM | Permanently Secured for Multiple Uses, including nature: Primary intention of the owner or easement holder for multiple uses. | Strong focus on recreational use, game species production, timber production, grazing and other uses in addition to these lands providing some biodiversity value. May include extractive uses of a broad, low-intensity type (e.g., some logging, grazing) or of a localized intense type (e.g., mining, military artillery testing area, public access beach area within large natural state park). Examples: recreation focused protected areas such as state parks, state recreation areas, wildlife management areas, game lands, state and national forests. |
| GAP 3, BLM lands | Permanently Secured for Multiple Uses, including nature: Primary intention of the owner or easement holder for multiple uses. | Lands owned by the Bureau of Land Management were placed in a separate category because of the higher level of use and mandate for grazing, mining, and other extractives uses on these lands which often leads to more potential impacts to the ecological systems on these lands. |

## *Regulating Function*

We based the level of regulating function protection for a reach on an assessment of the upstream watershed at three scales:

1) Percent of the upstream drainage area in conservation land,
2) Percent of the upstream river floodplain area in conservation land (see Chapter 3),
3) Percent of the local catchment in conservation land.

We accumulated the amount and percent of conservation land upstream for each scale (total drainage area, floodplain only, local catchment) using a flow accumulation function applied to the DEM. The scores were calculated while applying the appropriate weights to each type of conservation land (Table 5-2). For example, a reach with 100% of its total upstream area permanently secured for nature (GAP 2) received a score of 100, while a reach with 100% of its total upstream area in multiple use Bureau of Land Management land (GAP 3 BLM) received a score of 25 as these lands are open to mining and other extractive activities. Each of the three spatial scales had a possible maximum score of 100% and a minimum of zero.

**Table 5-2. Weighting of conservation land types by assessment unit to calculate the regulating function potential. BLM = U.S. Bureau of Land Management**

| Conservation Land Type | Upstream Drainage Area | Upstream Floodplain | Local Catchment |
|---|---|---|---|
| GAP 1 | 1 | 1 | 1 |
| GAP 2 | 1 | 1 | 1 |
| GAP 3, non-BLM | 1 | 1 | 1 |
| GAP3, BLM | 0.25 | 0.25 | 0.25 |

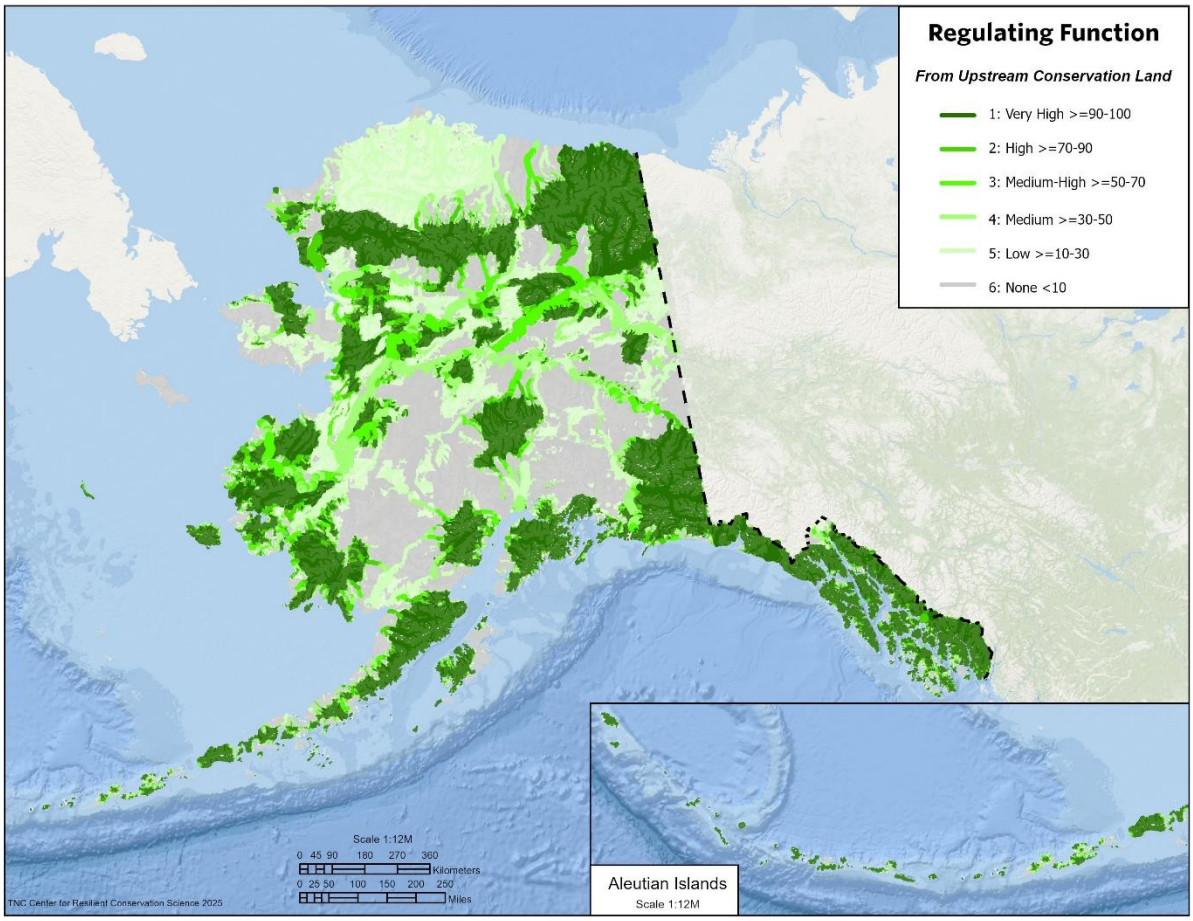
We calculated the overall regulating function score by integrating the three scales of assessment and various weights for the types of conservation lands (Table 5-3). First, we calculated the scores for each spatial scale, then we combined these into a single index giving 70% of the weight to the total upstream drainage area. The remaining 30% was distributed differently depending on the streams or river size. For larger rivers, we gave 20% to the floodplain score and 10% to the local catchment. For smaller rivers, we gave 10% to the floodplain score and 20% to the local catchment. For headwaters and creeks, we gave all 30% to the local catchment score.

**Table 5-3. Integration of the regulating function component metrics.**

| Regulating Function Score | Upstream Drainage Area | Upstream Floodplain | Local Catchment |
|---|---|---|---|
| Size 3 + rivers: >1,000 $km^2$ drainage area | 0.7 | 0.2 | 0.1 |
| Size 2 rivers: 100-1,000 $km^2$ drainage area | 0.7 | 0.1 | 0.2 |
| Streams < 100 $km^2$ drainage area | 0.7 | | 0.3 |

The final regulating index ranged between 0 and 100 and we report the data in six classes based on the natural break values developed for the conterminous U.S. (Anderson et al. 2023, Figure 5-5). For integration with the PRI, we converted all scores less than ten to zero, as inspection suggested they were not meaningful values for regulating function.

**Figure 5-5. Regulating function protection provided by conservation lands in a reach's upstream drainage area summarized by HUC-12 watershed.**




## Protection Class Score

To create an overall protection class score for each reach, we combined the PRI local protection score with the regulating function score, giving equal weight to each component and rescaling the result to be between 0 to 100. We group the scores into five protection classes by assigning a score of "No Protection" to all zeros and then dividing the remaining scores into equal interval groups where each bin included a quarter of the maximum possible score (Figure 5-6, Table 5-4).

**Figure 5-6. Protection class for streams and rivers.**

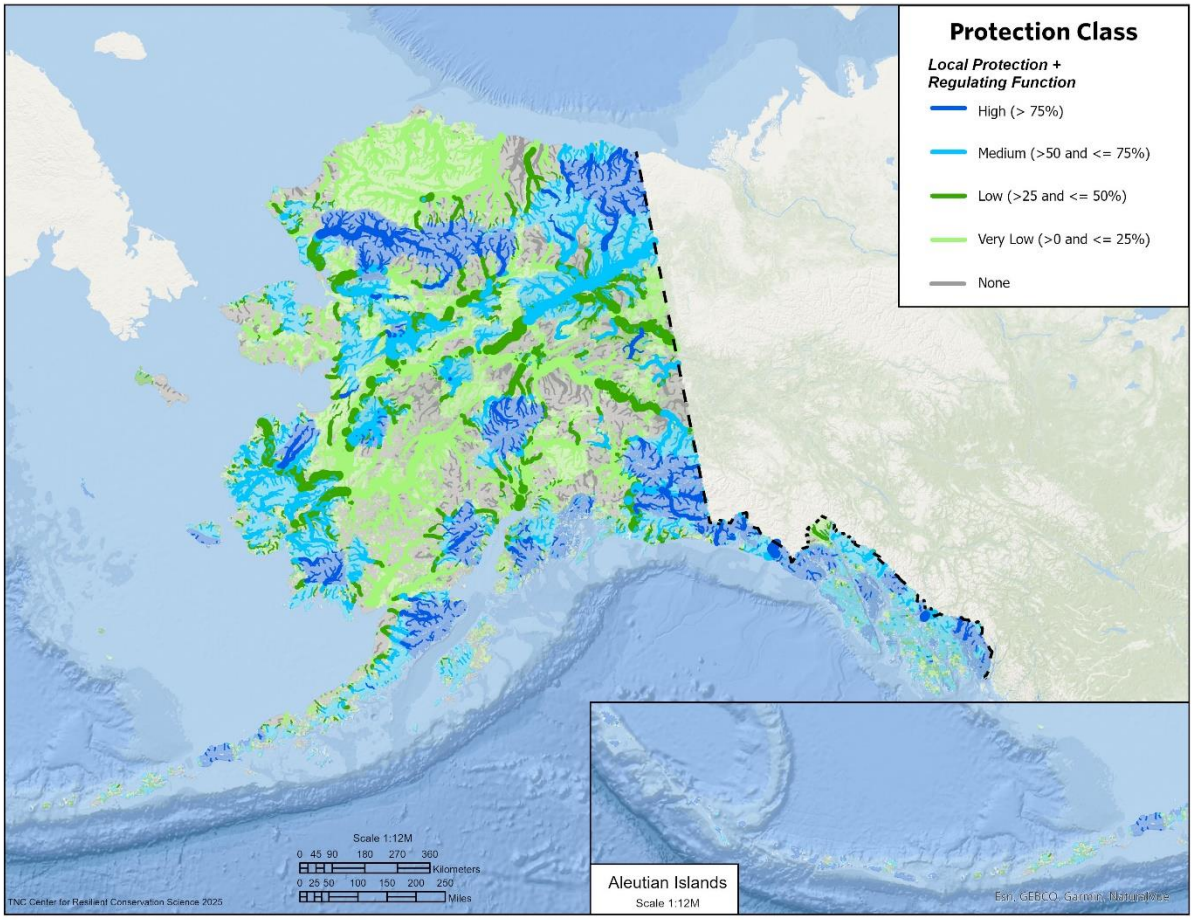



**Table 5-4. Percent of stream miles by protection class and by stream size.**

| Protection Class | Headwater Streams | Creek Streams | Small Rivers | Medium Rivers | Medium Mainstem Rivers | Large Rivers | Great Rivers | Total |
|---|---|---|---|---|---|---|---|---|
| 1. High (> 75%) | 17% | 16% | 15% | 11% | 9% | 2% | 0% | 16% |
| 2. Medium (>50 and <= 75%) | 26% | 26% | 25% | 22% | 28% | 17% | 14% | 25% |
| 3. Low (>25 and <= 50%) | 5% | 6% | 10% | 19% | 30% | 33% | 45% | 7% |
| 4. Very Low (>0 and <= 25%) | 27% | 30% | 35% | 42% | 33% | 48% | 40% | 30% |
| 5. None | 26% | 23% | 15% | 5% | 0% | 0% | 0% | 22% |
| Grand Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

# Conservation Status of the Freshwater Network

We combined the protection class dataset with the freshwater resilience results to answer the following questions: What is the conservation status of all rivers and streams in Alaska? What is the conservation status of the FRCN representing Alaska's most resilient and biodiverse rivers and streams?

## *Conservation Status for all Rivers and Streams*

Combining the seven resilience categories and five protection categories resulted in 34 unique combinations of classes. We simplified these into six major classes where "Restorable" equals average resilience and "Vulnerable" equals below-average resilience (Table 5-5).

Our results (Figure 5-7, Table 5-6) show that 39% of streams and rivers in Alaska are fully conserved in that they are both resilient and have protection (high or medium level of protection). Another 52% of streams and rivers are resilient but not protected (none to low protection). A third class has average or restorable resilience and is protected (1%) or not (5%). A fourth class has below-average resilience and is protected (1%) or not (2%).

**Table 5-5. Conservation status levels for all streams.**

| Resilience and Protection Class | Resilience | Protection | % Stream Miles |
|---|---|---|---|
| Resilient and Protected | Above Average | Medium – High | 32% |
| Resilient but Unprotected | Above Average | None - Low | 52% |
| Restorable and Protected | Average | Medium - High | 1% |
| Restorable and Unprotected | Average | None-Low | 5% |
| Vulnerable and Protected | Below Average | Medium – High | 1% |
| Vulnerable and Unprotected | Below Average | None-Low | 2% |

**Figure 5-7. Conservation status of all streams in Alaska based on freshwater resilience and level of protection.**

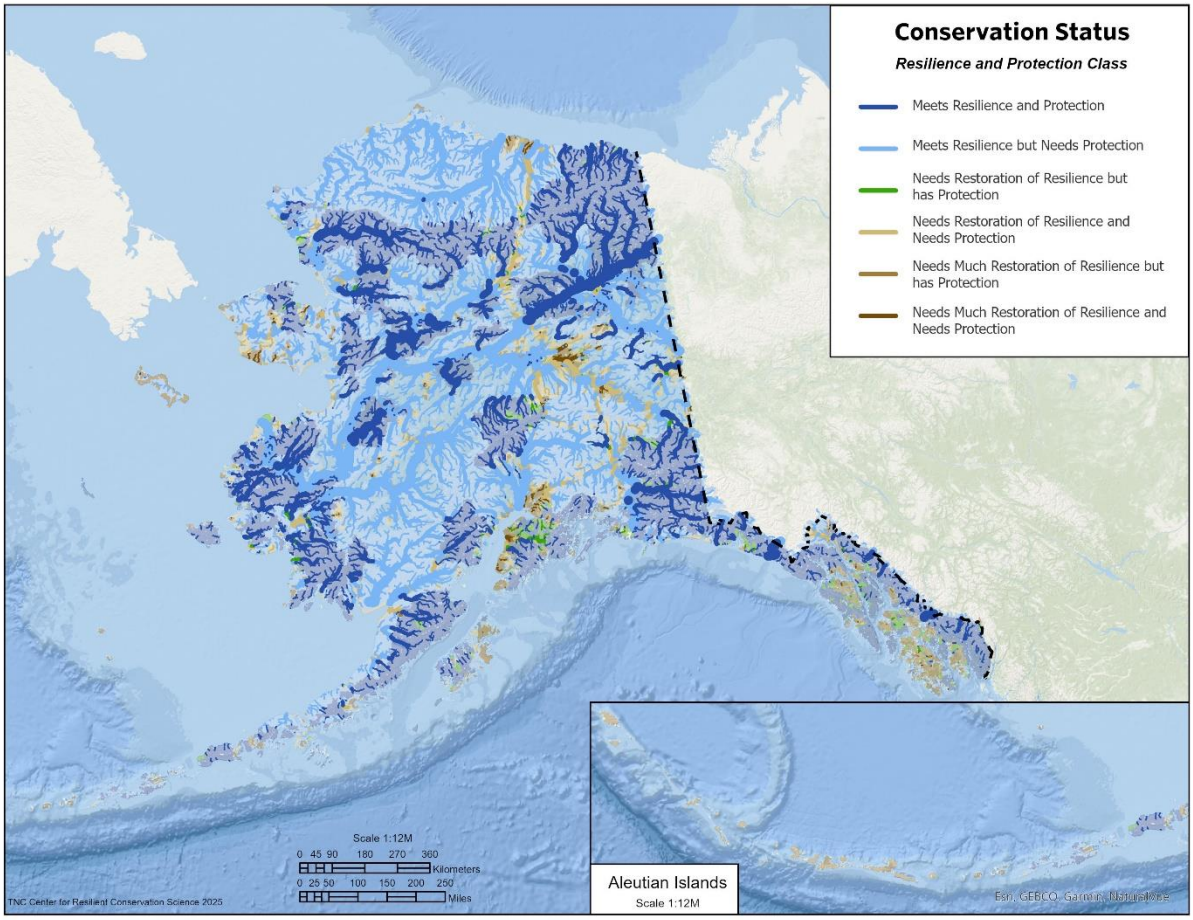
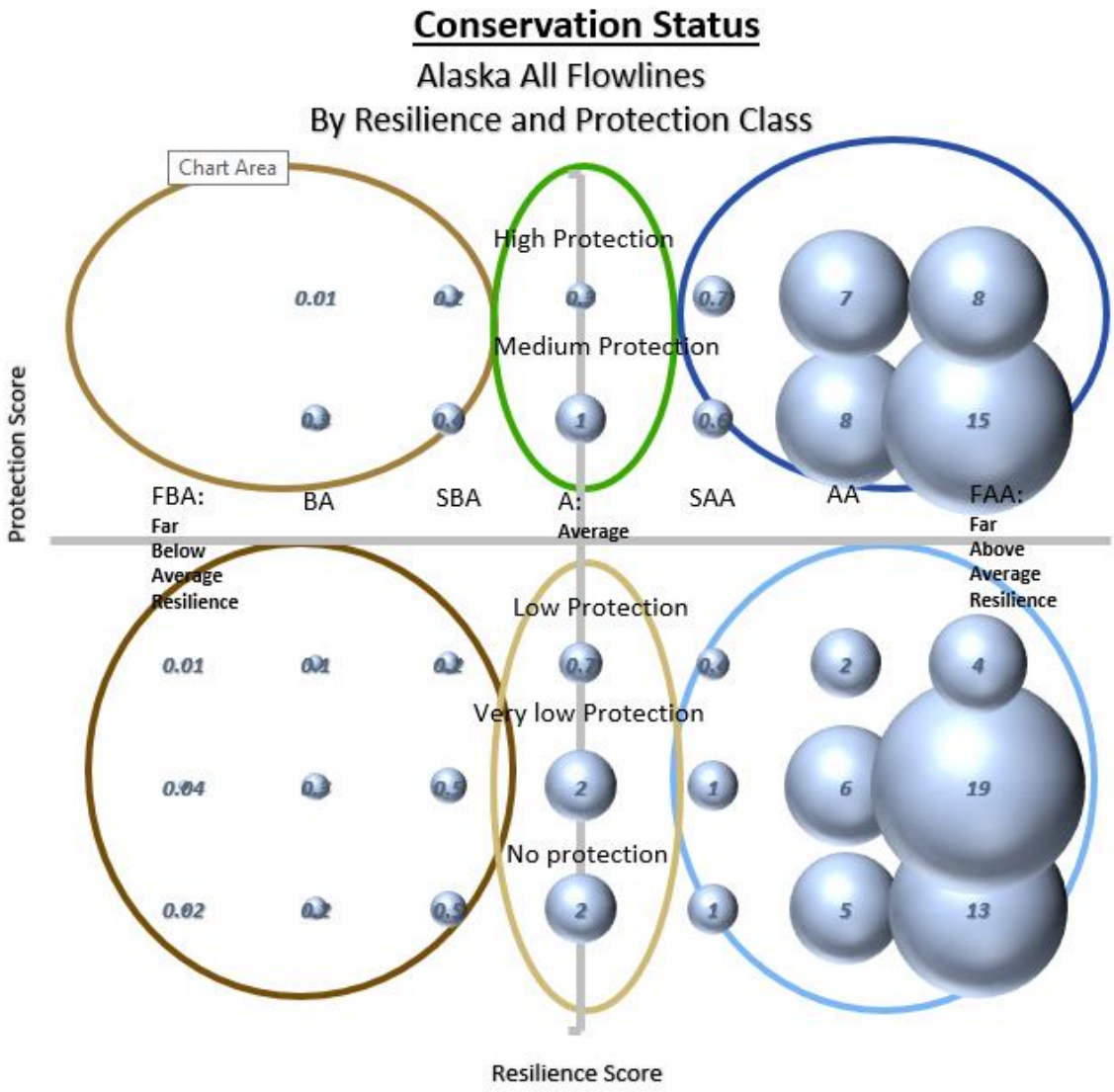



**Table 5-6. Conservation status of all rivers and streams by stream size.**

| Conservation Status Class | Headwater Streams | Creek Streams | Small Rivers | Medium Rivers | Medium Mainstem Rivers | Large Rivers | Great Rivers | Grand Total |
|---|---|---|---|---|---|---|---|---|
| Resilient and Protected | 40% | 39% | 38% | 32% | 36% | 19% | 14% | 39% |
| Resilient and Unprotected | 50% | 52% | 54% | 60% | 54% | 63% | 76% | 52% |
| Restorable and Protected | 1% | 1% | 1% | 1% | 1% | 0% | 0% | 1% |
| Restorable and Unprotected | 5% | 5% | 5% | 6% | 9% | 16% | 10% | 5% |
| Vulnerable and Protected | 1% | 1% | 0% | 0% | 0% | 0% | 0% | 1% |
| Vulnerable and Unprotected | 2% | 2% | 2% | 1% | 0% | 3% | 0% | 2% |
| Total | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** |

**Figure 5-8. The distribution of conservation status of all rivers and streams in Alaska.** The horizontal axis is the freshwater resilience score from "Far Below Average" (FBA) to "Far Above Average" (FAA) resilience. Average is centered. The vertical axis is the level of protection from low to high, using the six classes shown in Figure 5-7. The size of the sphere reflects the percentage of the stream reaches that fall into each category. Finally, the colored circles correspond to the conservation status groupings in

Table 5-6.



## *Conservation Status of the Freshwater Network*

Results show that 37% of streams and rivers in Alaska are fully conserved in that they are both resilient and have protection (high or medium level of protection). Another 55% of streams and rivers are resilient but not protected (none to low protection). A third class has average or restorable resilience and is protected (2%) while a fourth class of average of restorable resilience is unprotected (6%) (Figure 5-9,Figure 5-10 , Table 5-7). The Alaska FRCN is much more conserved than the FRCN for the conterminous U.S. (Figure 5-11).

**Figure 5-9. Conservation status of the Freshwater Resilient and Connected Network (FRCN) shown by resilience and protection class.**

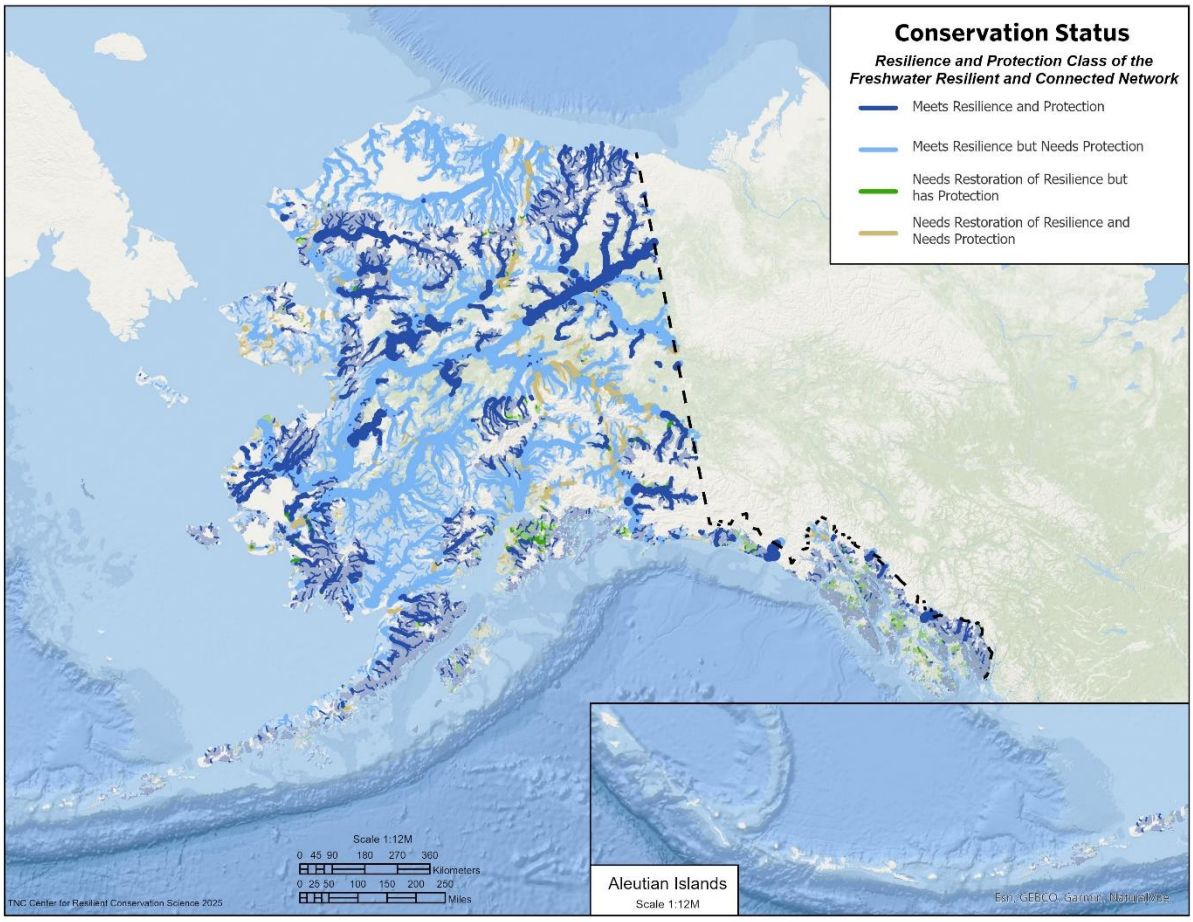


**Table 5-7. Conservation status of the freshwater resilient and connected network by stream size.**

| Conservation Status Class | Headwater Streams | Creek Streams | Small Rivers | Medium Rivers | Medium Mainstem Rivers | Large Rivers | Great Rivers | Grand Total |
|---|---|---|---|---|---|---|---|---|
| Resilient and Protected | 39% | 37% | 37% | 31% | 36% | 19% | 14% | 37% |
| Resilient and Unprotected | 53% | 55% | 57% | 61% | 55% | 64% | 76% | 55% |
| Restorable and Protected | 2% | 2% | 1% | 1% | 0% | 0% | 0% | 2% |
| Restorable and Unprotected | 6% | 6% | 5% | 7% | 9% | 16% | 10% | 6% |
| **Grand Total** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** | **100%** |

**Figure 5-10. The distribution of conservation status of the FRCN in Alaska.** The horizontal axis is the freshwater resilience score from "Far Below Average" (FBA) to "Far Above Average" (FAA) resilience. Average is centered. The vertical axis is the level of protection from low to high, using the six classes shown in Figure 5-7. The size of the sphere reflects the percentage of the stream reaches that fall into each category. Finally, the colored circles correspond to the conservation status groupings in

Table 5-6**.**

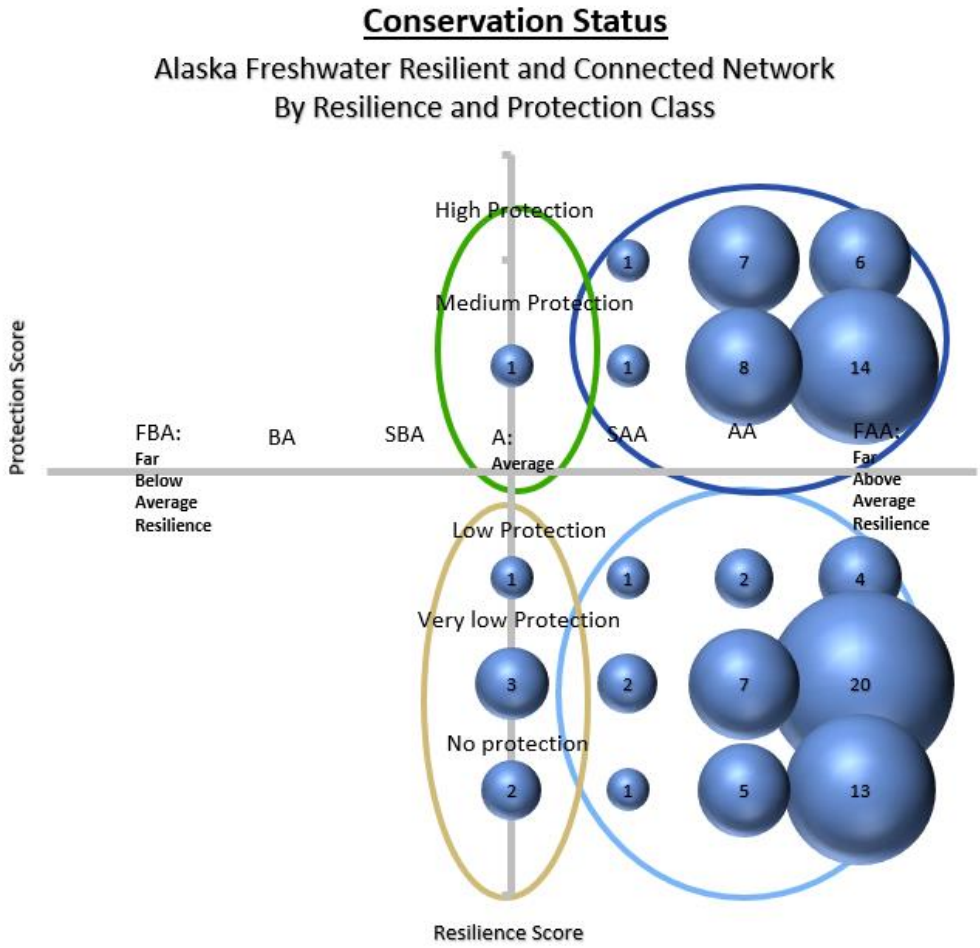
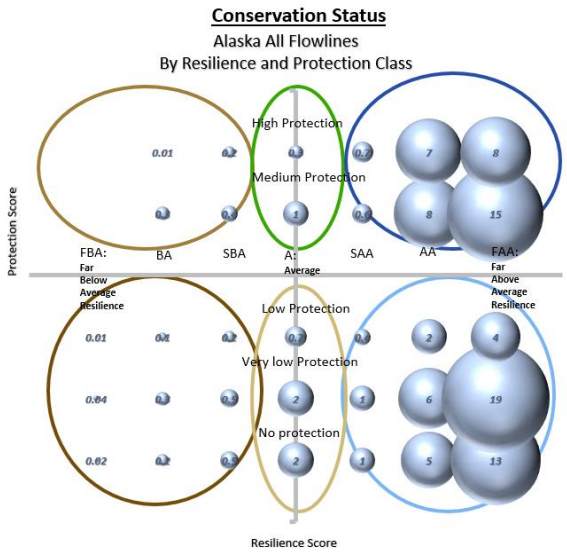
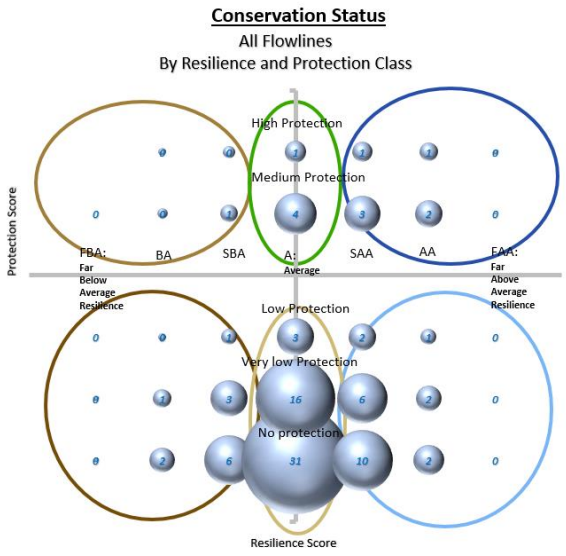


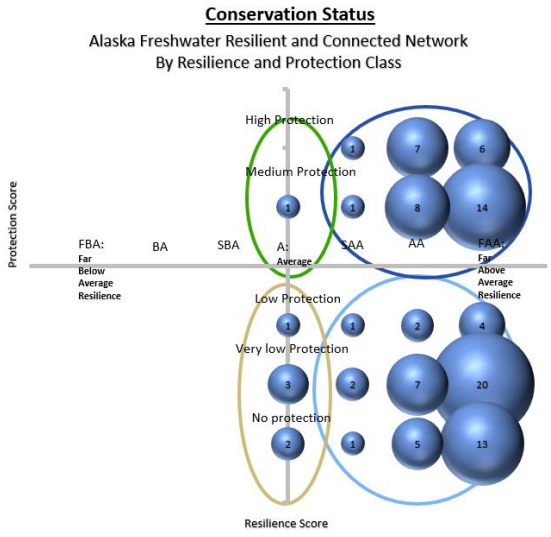
**Figure 5-11. Comparison of the conservation status of streams and FRCN between Alaska (left) and the conterminous U.S. (right)**



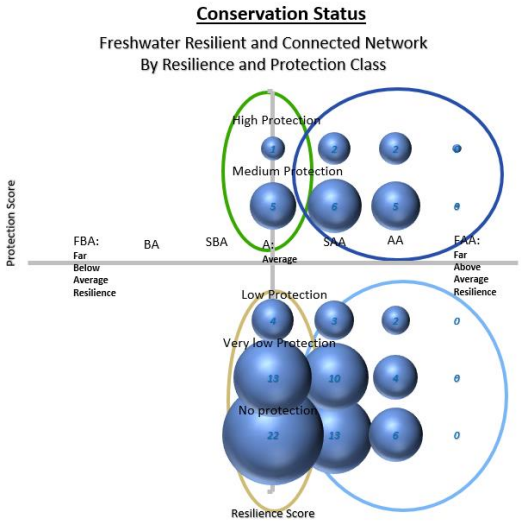

2025 AK Conservation Status




2025 CONUS Conservation Status




AK 2025 FRCN Conservation Status




CONUS 2024 FRCN and 2025 Conservation Status

CHAPTER

# Discussion 6

## Summary

The freshwater biota of Alaska evolved in free-flowing river networks that are still mostly intact, unlike the conterminous U.S. where over 150,000 dams now fragment the rivers and streams. While not free of climatic changes and other threats, our results suggest that in Alaska the enabling conditions exist for freshwater species to move and adapt to changing conditions and may explain why the state remains a salmon stronghold and retains its native fish fauna. Fragmentation, water withdrawal, ground water extraction, and water quality degradation are restricted to a small portion of the state associated with roads, towns, mines, and coastal settlements.

To help inform conservation action, we completed this one-year study to identify and map the characteristics that impart climate resilience to freshwater systems and assess the resilience of all streams and rivers in Alaska. Our methods followed those that we developed and applied to the conterminous U.S. (Anderson et al. 2023) allowing for a direct comparison. Physical factors included the size and diversity of each functionally connected network (FCN, river network bounded on all sides by dams, mouth, or source), and condition indicators such as floodplain conversion, impervious surface, presence of mining, and poor water quality. Water factors focused on altered hydrology. We compiled or developed Alaska-wide maps for each factor at the HUC-12 scale and then combined them into an integrated score using statistical transformations that equalized the mean and variance of each variable. A resilience score was calculated for each HUC-12 by combining the physical and water scores with ecologically appropriate weighting factors. Results identified 84% as having above average resilience (> 0.5 SD) as compared to 26% for the conterminous U.S.

A second goal of this study was to identify a set of resilient freshwater ecosystems that, if conserved, could potentially sustain the spectrum of aquatic biodiversity into the future. We identified this Freshwater Resilient and Connected Network (FRCN) by combining the continuous map of resilience with a map of freshwater sites recognized for their biodiversity per a compilation of several state-based biodiversity assessments. Using a definition of "restorable" for HUC-12s with average resilience and a single factor below-average, we distinguished a network of freshwater ecosystems encompassing 62% of Alaska's stream miles that were either biodiverse and resilient (57%) or biodiverse and restorable (5%). Another 24% were resilient but had not been recognized for biodiversity value, although this could reflect a lack of survey effort more than any difference in biodiversity.

While this is a riverine-focused analysis, the small watersheds identified include a wide array of essential freshwater features. Resilient networks comprise connected rivers with a diversity of temperature classes and macrohabitats, unfragmented headwaters, natural floodplains and/or riparian zones, surface and groundwater features as measured by wetlands, lakes, springs, and seeps, and many connections to the ocean. Accordingly, the FRCN does an excellent job of representing stream size classes, unimpeded river stretches, recognized

biodiversity areas, freshwater ecoregions, wetlands, and lakes and ponds. The latter features are also represented in the terrestrial RCN (Anderson et al. 2021), and we are exploring how to integrate the two networks. Conservation (both restoration and protection) of these river networks depends on and will benefit associated freshwater ecosystems but will not replace conservation action to benefit other types of freshwater habitats.

# Applying the Results

The intention of this analysis was to provide conservationists in the U.S. a means to evaluate the relative resilience of freshwater river networks for biodiversity in the face of a changing climate so action can be taken to maintain and improve resilience. The FRCN was intended to provide an initial filter to focus conservation efforts on the resilient and near-resilient rivers that have freshwater biodiversity significance and represent the diversity of river systems and aquatic species across CONUS and Alaska. We consider the FRCN to be an asset map of what we seek to conserve, not an action map to limit conservation and restoration work to the exact river catchments depicted on the map. Conservation of the network will involve multiple strategies including protection of resilient systems, restoration of flow and/or condition, and reconnecting small networks through barrier remediation, although these are initial filters that will require further study. The conservation actions that will make a difference to resilience are not prescriptive and we recommend a full assessment be made of ecological integrity and threats as outlined in Higgins et al. (2021).

To make the analysis and findings available to a broad range of audiences and support their interpretation and application by practitioners, we designed and launched the Resilient River Explorer web tool (RRE, https://maps.tnc.org/resilientrivers). Along the top banner of the tool are links to several resources including a brief user guide, feedback forms, data downloads, and map service links for GIS users. The tool is organized into five thematic sections, each corresponding to a different way to use the results and accessible via tabs at the top of the page.

- The **Elements** tab is the starting point for new users of the tool. It provides an overview of the core concepts and datasets used in the analysis and sets the stage for users to dive deeper into the data in the subsequent tabs.

- The **Explore** tab is designed to help users understand how the various components of resilience come together into the final resilience score for any given location. This tab is also the most open-ended section of the tool, with reference and source-data layers available to view and provide context for the resilience score.

- The **Assess a River** tab summarizes the resilience results for a named river based on the HUC-12 scores. In addition to summarizing the results for a river, the "opportunities" subsection of this tab highlights spatially explicit conservation actions that have the potential to maintain or restore the resilience of the selected river.

- The **Terrestrial** tab incorporates TNC's terrestrial resilience data (Anderson et al. 2023) into the map and summarizes it for each of the freshwater resilience units (HUC-12s, FCNs, and their floodplains). While short of a full integration of the terrestrial and freshwater resilience

data, these summaries can help users evaluate potential synergies between freshwater and terrestrial resilience in any given location.

- The **Scenarios** tab allows users to dynamically assess potential improvements to resilience that could be realized by removing one or more dams. Selecting a dam for removal in this tab triggers the recalculation of the connectivity and resilience scores to show the approximate impact of dam removal(s) on overall resilience. Additional scenario testing capabilities may be added in the future to model and evaluate other conservation actions.

# Data Limitations and Future Analysis

This analysis used current, comprehensive river and land data for Alaska and parts of Canada that supported a robust analysis. That said, the scale of the analysis created limitations in what data could be used because we needed consistency across the study area to avoid spatial bias from data discrepancies. For example, given the lack of consistent inventories of small dams on streams and headwaters, we know there are most certainly additional dams beyond what we included in this analysis. Despite the variation in the scales of the input data and metrics, we sought to use the appropriate summary scale for each metric and to combine variables in a logical multi-scale framework. The resilience value of each analysis unit thus integrated local condition information with the size of the larger connected network within which a HUC occurred.

Our measure of freshwater resilience is relative. We defined resilience as the ability of freshwater ecosystems to adapt, adjust, and maintain biological diversity in a changing climate. Our hypothesis for mapping freshwater resilience was that the physical setting and its condition, together with water availability and its alteration, drive resilience in freshwater systems by providing habitat options and the integrity to maintain ecological function. Supported by evidence, our assumption was that networks with more of these characteristics will be relatively more resilient than ecologically similar networks with less of these characteristics. However, there is not a specific threshold that guarantees a river is resilient. Thus, a river that is in our top class of resilience may still have restoration needs.

The resilience analysis and the FRCN are intended to be used with local information or other spatial and descriptive data to inform conservation action. The type of additional information depends on the questions one wants to answer. As an example, TNC's Appalachian freshwater team, working with representatives from federal agencies, wanted to query a suite of ecological and socioeconomic data to identify watersheds in the Appalachians where restoration of freshwater connectivity (dam removal, culvert replacements, etc.) could benefit both nature and people. The resulting Reconnecting America's Waterways tool (RAW, https://www.maps.tnc.org/raw) incorporates the freshwater resilience results with data on biodiversity, barriers, and disadvantaged communities at risk from future flooding.

# A Final Note

The purpose of this report was to provide transparency into our methods such that natural resource managers, conservation planners, and practitioners can confidently integrate the results we have offered with other important values, such as human climate resilience, to achieve lasting conservation impact. The results and much of the underlying data are accessible and available for download through the Resilient River Explorer. We acknowledge that equity for people is not represented in this analysis as we were focused on the other species with which we share the planet, and who also need abundant clean freshwater. We recognize, however, that maps give values to lands and waters and are not neutral about human equity – both in what is interpreted to be important for conservation action, the sourcing of the data used, and who participated in the analysis. Reference layers representing human dimensions could be added in the future as we have explored with the Reconnecting America's Waterways tool described above. Freshwater biodiversity resilience to climate change is essential to people, and while not the only measure of meaningful conservation, it is an essential ingredient to our conservation success.

# References


Abell, R., Thieme, M. L., Revenga, C., Bryer, M., Kottelat, M., Bogutskaya, N., ... & Petry, P. 2008. Freshwater ecoregions of the world: a new map of biogeographic units for freshwater biodiversity conservation. BioScience, 58(5), 403-414.

Abell, R., Lehner, B., Thieme, M. and Linke, S., 2017. Looking beyond the fenceline: Assessing protection gaps for the world's rivers. *Conservation Letters*, *10*(4), pp.384-394.

Abramovitz, J.N, A. Ancharya. 1996. Imperiled Waters, Impoverished Future: The Decline of Freshwater Ecosystems. Worldwatch Paper, 128. J.A. Peterson, editor. Worldwatch Institute. 80 p.

Alaska Department of Environmental Conservation (ADEC). 2020. Alaska Nonpoint Source Water Pollution Prevention and Restoration Strategy https://dec.alaska.gov/media/21608/final-ak-fy21-25-nps-strategy.pdf Accessed 9/10/24.

Alaska Department of Environmental Conservation (ADEC). 2024. Alaska 303(d) Impaired Waters. https://gis.data.alaska.gov/maps/ADEC::alaska-dec-impaired-waters/about?layer=0 Accessed 10/15/24.

Alaska Department of Environmental Conservation (ADEC). 2025. Alaska Regulated Contaminated Sites. https://gis.data.alaska.gov/datasets/ADEC::alaska-dec-contaminated-sites/explore?location=58.849628%2C-156.412240%2C5.69 Accessed 2/20/25.

Alaska Department of Environmental Conservation (ADEC). 2025. Groundwater In Alaska. https://dec.alaska.gov/eh/dw/resources/groundwater-in-alaska/ Accessed 6/14/2025.

Alaska Department of Transportation & Public Facilities. 2025. Superfund Site Boundaries. https://alaska-critical-infrastructure-akdot.hub.arcgis.com/datasets/superfund-sites-boundaries-1/explore?location=13.230524%2C-0.355538%2C1.88 Accessed 2/20/25.

Alaska Freshwater Fish Inventory. 2024. Fish Species Reports. https://www.adfg.alaska.gov/index.cfm?adfg=animals.listfish&sort=scientific

Aho, K.B., Flotemersch, J.E., Leibowitz, S.G., LaCroix, M.A. and Weber, M.H., 2020. Applying the index of watershed integrity to the Matanuska–Susitna basin. *Arctic, antarctic, and alpine research*, *52*(1), pp.435-449.

Alaska Center for Conservation Science. Alaska Vegetation and Wetland Composite dataset. Accessed 2022 https://accscatalog.uaa.alaska.edu/dataset/alaska-vegetation-and-wetland-composite

Alaska Department of Fish and Game Division of Sport Fish RTS. 2024. Catalog of Waters Important for Spawning, Rearing or Migration of Anadromous Fishes. https://www.adfg.alaska.gov/sf/SARR/AWC/index.cfm?ADFG=maps.dataFiles

Alaska Hydrologic Survey – Division of Mining, Land, and Water. 2025. Alaska Surface Water Facts. Alaska Groundwater Facts. https://dnr.alaska.gov/mlw/water/hydro/ accessed 6/20/2025

Alexander, L.C., Fritz, K.M., Schofield, K.A., Autrey, B.C., DeMeester, J.E., Golden, H.E., Goodrich, D.C., Kepner, W.G., Kiperwas, H.R., Lane, C.R., LeDuc, S.D., Leibowitz, S.G., McManus, M.G., Pollard, A.I., Ridley, C.E., Vanderhoof, M.K., and Wigington, P.J. 2018. Featured Collection Introduction: Connectivity of Streams and Wetlands to Downstream Waters. Journal of the American Water Resources Association, 54(2), 287–297. https://doi.org/10.1111/1752-1688.12630.

Allan, J. D. 1995. Stream Ecology: Structure and function of running waters. Kluwer Academic Publishers. Dordrecht, The Netherlands.

Alofs, K.M., Jackson, D.A., & Lester, N.P. 2014. Ontario freshwater fishes demonstrate differing range-boundary shifts in a warming climate. Diversity and Distributions, 20, 123–136. https://doi.org/10.1111/ddi.12130

Anderson, M.G., Clark, M., & Sheldon, A.O. 2014. Estimating Climate Resilience for Conservation across Geophysical Settings. *Conservation Biology*, 28(4), 959–970. https://doi.org/10.1111/cobi.12272

Anderson, M.G., A. Barnett, M. M. Clark, J. DePasquale, A. Olivero, J. Prince, and C. Shanley. 2022. Resilient Sites and Connected Landscapes for Terrestrial Conservation in Alaska. The Nature Conservancy, Center for Resilient Conservation Science.

Anderson M.G, Clark M., Olivero A.P., Barnett A.R., Hall K.R., Cornett M.W., Ahlering M., Schindel M., Unnasch B., Schloss C., Cameron D.R. 2023. A resilient and connected network of sites to sustain biodiversity under a changing climate. Proc Natl Acad Sci, 120(7):e2204434119. doi: 10.1073/pnas.2204434119.

Anderson, M.G., Olivero, A.P., Barnett, A.R., Khoury, M.L., and Martin, E.H. 2024. Mapping Freshwater Resilience across the Conterminous U.S. The Nature Conservancy, Center for Resilient Conservation Science. Newburyport, MA.

Armstrong, J.B., Fullerton, A.H., Jordan, C.E., Ebersole, J.L., Bellmore, J.R., Arismendi, I., Penaluna, B.E. and Reeves, G.H., 2021. The importance of warm habitat to the growth regime of cold-water fishes. Nature Climate Change, 11(4), pp.354-361.

Beck, Hylke E.; E. Zimmermann, Niklaus; McVicar, Tim R.; Vergopolan, Noemi; Berg, Alexis; Wood, Eric F. (2018): Present and future Köppen-Geiger climate classification maps at 1-km resolution. figshare. https://doi.org/10.6084/m9.figshare.6396959
Beier, P., & Brost, B. 2010. Use of land facets to plan for climate change: conserving the arenas, not the actors. Conservation Biology, 24(3), 701–710. https://doi.org/10.1111/j.1523-1739.2009.01422.x

Beichen Zhang, Junzhi Liu*, Bin Zhang, Dawei Xiao, Min Chen. 2024. A web-based tool for watershed delineation considering lakes and reservoirs, Environmental Modelling & Software, 183, 106232 (doi.org/10.1016/j.envsoft.2024.106232)

Bowler, D. E., Mant, R., Orr, H., Hannah, D. M., and Pullin, A. S. 2012. What are the effects of wooded riparian zones on stream temperature? Environmental Evidence, 1(1), 1–9. https://doi.org/10.1186/2047-2382-1-3.

Burkhead, N. M. 2012. Extinction Rates in North American Freshwater Fishes, 1900 – 2010. BioScience, 62(9), 798–808. https://doi.org/10.1525/bio.2012.62.9.5

Callegary, J.B., Kikuchi, C.P., Koch, J.C., Lilly, M.R. and Leake, S.A., 2013. groundwater in Alaska (USA). Hydrogeology Journal, 21(1), p.25.

Center for Watershed Protection (CWP). 2003. Impacts of Impervious Cover on Aquatic Systems. Watershed Protection Research monograph No. 1.

Chithra, S.V., Harindranathan Nair, M.V., Amarnath, A., and Anjana, N.S. 2015. Impacts of Impervious Surfaces on the Environment. International Journal of Engineering Science Invention, 4(5), 27–31.

Comte, L., and Grenouillet, G. 2013. Do stream fish track climate change? Assessing distribution shifts in recent decades. Ecography, 36(11), 1236–1246. https://doi.org/10.1111/j.1600-0587.2013.00282.x

Comte, L., Murienne, J., and Grenouillet, G. 2014. Species traits and phylogenetic conservatism of climate-induced range shifts in stream fishes. Nature Communications, 5, 5053. https://doi.org/10.1038/ncomms6053

Conservation Science Partners (CSP). 2025. Protected Rivers Assessment of the United States - Final Report. Truckee, California, USA.

Cooper, A.R., Infante, D.M., Daniel, W.M., Wehrly, K.E., Wang, L., and Brenden, T.O. 2017. Assessment of dam effects on streams and fish assemblages of the conterminous USA. Science of the Total Environment, 586, 879–889. https://doi.org/10.1016/j.scitotenv.2017.02.067

de Mello K., Valente R.A, Randhir T.O., Alves dos Santos A.C., and Vettorazzi C.A. 2018. Effects of land use and land cover on water quality of low-order streams in southeastern

Brazil: watershed versus riparian zone. Catena 167: 130-138. https://doi.org/10.1016/j.catena.2018.04.027.

Dewitz, J., 2020. National Land Cover Database (NLCD) 2016 - Alaska). U.S. Geological Survey data release, https://doi.org/10.5066/P96HHBIE.

Eby, L.A., Helmy, O., Holsinger, L.M., & Young, M.K. 2014. Evidence of Climate-Induced Range Contractions in Bull Trout *Salvelinus confluentus* in a Rocky Mountain. PLOSone, 9(6), 1–8. https://doi.org/10.1371/journal.pone.0098812

Esselman, P., Infante, D., Wang, L., Cooper, A., Wieferich, D., Tsang, Y., Thornbrugh, D., and Taylor, W. 2013. Regional fish community indicators of landscape disturbance to catchments of the conterminous United States. Ecological Indicators. 26. 163–173. 10.1016/j.ecolind.2012.10.028.

U.S. Environmental Protection Agency. 2022. NPDES Outfalls Regulated Facilities. https://www.arcgis.com/home/item.html?id=1a09c54d5e0141558a5cfbab635b90b6 Accessed 2/20/25.

Fitzhugh, T. W., & Vogel, R. M. (2011). The impact of dams on flood flows in the United States. River Research and Applications, 27(10), 1192–1210. https://doi.org/10.1002/rra.1417

Flitcroft, R., Whitman, L., White, J., Wallick, R., Garvin, L.S., Smith, C., Plotnikoff, R., Mulvey, M., Kock, T., Jones, K. and Gruendike, P., 2023. Science to support conservation action in a large river system: The Willamette River, Oregon, USA. Water Biology and Security, 2(4), p.100203.

Geist, M., M. Aisu , P. Lema, E. J. Trammell. 2017, updated 2024, "Mining Footprint across Alaska and Northwest Canada". Alaska Center for Conservation Science, University of Alaska Anchorage

Grill, G., Lehner, B., Thieme, M., Geenen, B., Tickner, D., Antonelli, F., Babu, S., Borrelli, P., McClain, M. E., et al. (2019). Mapping the world's free-flowing rivers. Nature, 569(7755), 215–221. https://doi.org/10.1038/s41586-019-1111-9

Hall, J.V., Frayer, W.E. and Wilen, B.O., 1994. Status of Alaska wetlands. US Fish & Wildlife Service, Alaska Region.

Higgins, J.V., Bryer, M.T., Khoury, M.L. and Fitzhugh, T.W. 2005. A Freshwater Classification Approach for Biodiversity Conservation Planning. Conservation Biology, 19, 432-445. https://doi.org/10.1111/j.1523-1739.2005.00504.x

Higgins, J., Zablocki, J., Newsock, A., Krolopp, A., Tabas, P., & Salama, M. 2021. Durable freshwater protection: A framework for establishing and maintaining long-term protection for freshwater ecosystems and the values they sustain. Sustainability (Switzerland), 13(4), 1–17. https://doi.org/10.3390/su13041950

Hill, R.A., Weber, M.H., Leibowitz, S.G., Olsen, A.R. & Thornbrugh, D.J. 2016. The Stream-Catchment (StreamCat) Dataset: A database of watershed metrics for the conterminous United States. J Am Water Resour Assoc 52, 120–128.

Hill, R.A., Hawkins, C.P., & Carlisle, D.M. 2013. Predicting thermal reference conditions for USA streams and rivers. Freshwater Science, 32(1), 39-55. https://www.journals.uchicago.edu/doi/full/10.1899/12-009.1

Hill, R.A., Hawkins, C.P., and Jin, J. 2014. Predicting thermal vulnerability of stream and river ecosystems to climate change. Climatic Change 125(3): 399-412

Holland, M.M. and Landrum, L., 2021. The emergence and transient nature of Arctic amplification in coupled climate models. Frontiers in Earth Science, 9, p.719024.

IUCN. 2023a. Freshwater fish highlight escalating climate impacts on species - IUCN Red List. https://www.iucn.org/press-release/202312/freshwater-fish-highlight-escalating-climate-impacts-species-iucn-red-list. Accessed on February 20, 2014.

Lehner, B., Beames, P., Mulligan, M., Zarfl, C., De Felice, L., van Soesbergen, A., Thieme, M., et al. 2024. The Global Dam Watch database of river barrier and reservoir information for large-scale applications. Scientific Data, 11(1), 1069. https://doi.org/10.1038/s41597-024-03033-2

Littell, J., Reynolds, J.H., Bartz, K.K., McAfee, S.A. and Hayward, G.D., 2023. So goes the snow: Alaska snowpack changes and impacts on pacific salmon in a warming climate. Alaska Park Science, 19(1), pp.62-75.

Johnson, T.B., and D.O. Evans. 1990. Size-dependent winter mortality of young-of-the-year white perch: climate warming and invasion of the Laurentian Great Lakes. Transactions of the American Fisheries Society, 119(2):301–313

Jorgenson, K.L., Douglas, T.A., Jorgenson, M.T., Pastick, N.J. and Harms, T.K., 2025. Permafrost and rain influence summer hydrologic flowpaths in boreal catchments. Water Resources Research, 61(6), p.e2024WR039024.

Karp, M.A., Peterson, J.O., Lynch, P.D., Griffis, R.B., Adams, C.F., Arnold, W.S., Barnett, L.A. K., Dicosimo, J., Fenske, K.H., Gaichas, S.K., Hollowed, A., Holsman, K., Karnauskas, M., Kobayashi, D., Leising, A., Manderson, J.P., Mcclure, M., Morrison, W.E., Schnettler, E.,

Karjalainen, O., Aalto, J., Luoto, M., Westermann, S., Romanovsky, V.E., Nelson, F.E., Etzelmüller, B. and Hjort, J., 2019. Circumpolar permafrost maps and geohazard indices for near-future infrastructure risk assessments. *Scientific Data*, *6*(1), pp.1-16.

Kaufmann, P.R., Hughes, R.M., Paulsen, S.G., Peck, D.V., Seeliger, C.W., Weber, M.H., & Mitchell, R.M. 2022a. Physical habitat in conterminous US streams and rivers, Part 1:

Geoclimatic controls and anthropogenic alteration. Ecological Indicators, 141(January), 109046. https://doi.org/10.1016/j.ecolind.2022.109046

Koch, J. C. Y. Sjoberg, J. O'Donnell, M. Carey, P. F. Sullivan and A. Terskaia. 2022. Sensitivity of headwater streamflow to thawing permafrost and vegetation change in a warming Arctic. Environmental Research Letters 17(4): 044074

Koch, J. C., Poulin, B. A., O'Donnell, J. A., Carey, M. P. and Evinger, T., 2023, Chemistry of orange and reference streams in northwestern Alaska: U.S. Geological Survey data release, https://doi.org/10.5066/P9DZSQ43.

Kunkel, K.E., Frankson, R., Runkle, J., Champion, S.M., Stevens, L.E., Easterling, D.R., Stewart, B.C., McCarrick, A. and Lemery, C.R., 2022. State Climate Summaries for the United States 2022. NOAA Technical Report NESDIS 150. NOAA NESDIS.

Lehner, B., Messager, M. L., Korver, M. C., & Linke, S. 2022. Global hydro-environmental lake characteristics at high spatial resolution. Scientific Data, 9, 351. https://doi.org/10.1038/s41597-022-01425-z 1

Lehner, Bernhard; Beames, Penny; Mulligan, Mark; Zarfl, Christiane; De Felice, Luca; van Soesbergen, Arnout; et al. (2024). Global Dam Watch database version 1.0. figshare. Dataset. https://doi.org/10.6084/m9.figshare.25988293.v1

Li, J., Zhao, C., Chen, A., Zhang, H. and Yang, Y., 2024. Advances in understanding the mechanisms of Arctic amplification. Science China Earth Sciences, pp.1-16.

Link, J.S. 2019. Food for thought: accounting for shifting distributions and changing productivity in the development of scientific advice for fishery management. ICES Journal of Marine Science, 76(March), 1305–1315. https://doi.org/10.1093/icesjms/fsz048

Linke, S., Lehner, B., Ouellet Dallaire, C., Ariwi, J., Grill, G., Anand, M., Beames, P., Burchard-Levine, V., Maxwell, S., Moidu, H., Tan, F., & Thieme, M. 2019. Global hydro-environmental sub-basin and river reach characteristics at high spatial resolution. Scientific Data, 6, 283. https://doi.org/10.1038/s41597-019-0300-6

Lynch, A. J., Cooke, S. J., Arthington, A. H., Baigun, C., Bossenbroek, L., Dickens, C., Harrison, I., Kimirei, I., Langhans, S. D., Murchie, K. J., Olden, J. D., Ormerod, S. J., Owuor, M., Raghavan, R., Samways, M. J., Schinegger, R., Sharma, S., Tachamo-Shah, R. D., Tickner, D., … Jähnig, S. C. 2023. People need freshwater biodiversity. Wiley Interdisciplinary Reviews: Water, 10(3), 1–31. https://doi.org/10.1002/wat2.1633

Lynch, A.J., Myers, B. J.E., Chu, C., Eby, L.A., Falke, J.A., Kovach, R.P., Krabbenhoft, T.J., Kwak, T.J., Lyons, J., Paukert, C.P., & Whitney, J.E. 2016. Climate Change Effects on North American Inland Fish Populations and Assemblages. Fisheries, 41(7), 346–361. https://doi.org/10.1080/03632415.2016.1186016

McElfish, J.A. 2023. What Comes Next for Clean Water? Six Consequences of Sackett v. EPA. Environmental Law Institute. https://www.eli.org/vibrant-environment-blog/what-comes-next-clean-water-six-consequences-sackett-v-epa. Accessed September 18, 2024.

Martin, E. H. and J. Levine. 2017. Northeast Aquatic Connectivity Assessment Project - Version 2.0: Assessing the ecological impact of barriers on Northeastern rivers. The Nature Conservancy, Brunswick, Maine. http://maps.freshwaternetwork.org/northeast/

Mayer, T. D., & Naman, S. W. 2011. Streamflow response to climate as influenced by geology and elevation. Journal of the American Water Resources Association, 47(4), 724–738. https://doi.org/10.1111/j.1752-1688.2011.00537.x

McManamay, R.A. and DeRolph, C.R. 2019. A stream classification system for the conterminous United States. Scientific Data, 6(1), pp.1-18.

McManamay, R. A., George, R., Morrison, R. R., & Ruddell, B. L. 2022. Mapping hydrologic alteration and ecological consequences in stream reaches of the conterminous United States. Scientific Data, 9, 450. https://doi.org/10.1038/s41597-022-01566-1

Michalek, A.T., Villarini, G., Prein, A.F., Done, J.M., Johnson, D.R. and Wang, C., 2025. Precipitation-and temperature-driven future changes to flooding in Alaska. *Geophysical Research Letters*, *52*(3), p.e2024GL112004.

Mizukami, N., Newman, A.J., Littell, J.S., Giambelluca, T.W., Wood, A.W., Gutmann, E.D., Hamman, J.J., Gergel, D.R., Nijssen, B., Clark, M.P. and Arnold, J.R., 2022. New projections of 21st century climate and hydrology for Alaska and Hawaiʻi. Climate Services, 27, p.100312.

Murphy, J. 2020. Changing suspended sediment in United States rivers and streams: linking sediment trends to changes in land use/cover, hydrology, and climate. Hydrol. Earth Syst. Sci., 24, 991–1010, 2020. https://doi.org/10.5194/hess-24-991-2020

O'Donnell, J.A., Carey, M.P., Koch, J.C. et al. Metal mobilization from thawing permafrost to aquatic ecosystems is driving rusting of Arctic streams. Commun Earth Environ 5, 268 (2024). https://doi.org/10.1038/s43247-024-01446-z

Oke, K.B., Cunningham, C.J., Westley, P.A.H., Baskett, M.L., Carlson, S.M., Clark, J., Hendry, A.P., Karatayev, V.A., Kendall, N.W., Kibele, J. and Kindsvater, H.K., 2020. Recent declines in salmon body size impact ecosystems and fisheries. Nature communications, 11(1), p.4155.

Olivero, A.P., and M. Clark. 2024. Secured Areas by Gap Status and Type. Center for Resilient Conservation Science, The Nature Conservancy. https://tnc.maps.arcgis.com/home/item.html?id=5686424360814955a7d40ce1c2442549

Ouellet Dallaire, C., Lehner, B., Sayre, R., Thieme, M. (2019). A multidisciplinary framework to derive global river reach classifications at high spatial resolution. Environmental Research Letters, 14(2): 024003. https://doi.org/10.1088/1748-9326/aad8e9

Paukert, C., Olden, J.D., Lynch, A.J., Breshears, D.D., Christopher Chambers, R., Chu, C., Daly, M., Dibble, K.L., Falke, J., Issak, D., Jacobson, P., Jensen, O. P., & Munroe, D. 2021. Climate change effects on North American fish and fisheries to inform adaptation strategies. Fisheries, 46(9), 449–464. https://doi.org/10.1002/fsh.10668

Patro, E. R., Ghadimi, S., Shahrood, A. J., Fazel, N., Makarieva, O., & Torabi Haghighi, A. 2023. Flow regime alteration in Arctic rivers due to dam operations and climate change. Science of The Total Environment, Article 1728045. https://doi.org/10.1016/j.scitotenv.2023.1728045

Pelletier, M. C., Ebersole, J., Mulvaney, K., Rashleigh, B., Gutierrez, M. N., Chintala, M., Kuhn, A., Molina, M., Bagley, M., & Lane, C. 2020. Resilience of aquatic systems: Review and management implications. Aquatic Sciences, 82(2), 1–44. https://doi.org/10.1007/s00027-020-00717-z.

Pennock, C.A., Budy, P., Macfarlane, W.W., Breen, M.J., Jimenez, J., & Schmidt, J.C. 2022. Native fish need a natural flow regime. Fisheries, 47(3), 118–123. https://doi.org/10.1002/fsh.10703.

Peterson, R.A. 2021. Finding Optimal Normalizing Transformations via bestNormalize. The R Journal, 13:1, 310-329, DOI:10.32614/RJ-2021-041

Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E. and Stromberg, J.C., 1997. The natural flow regime. BioScience, 47(11), pp.769-784.

Possingham, H.P., Bode, M. and Klein, C.J., 2015. Optimal conservation outcomes require both restoration and protection. PLoS biology, 13(1), p.e1002052.
Pringle, C. 2003. What is hydrologic connectivity and why is it ecologically important? Hydrological Processes, 17(13), 2685–2689. https://doi.org/10.1002/hyp.5145.

Pringle, C. 2003. What is hydrologic connectivity and why is it ecologically important? *Hydrological Processes*, 17(13), 2685–2689. https://doi.org/10.1002/hyp.5145.

R Core Team. 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rosgen, D.L. 1996. Applied River Morphology. Wildland Hydrology, Pagosa Springs, CO

Russi D., ten Brink P., Farmer A., Badura T., Coates D., Förster J., Kumar R. and Davidson N. (2012) The Economics of Ecosystems and Biodiversity for Water and Wetlands. Final Consultation Draft.

https://www.ramsar.org/sites/default/files/migration_files/documents/pdf/TEEB/TEEB_Water-Wetlands_Final-Consultation-Draft.pdf

Southern Aquatic Resource Partnership (SARP). 2024. Alaska Barriers. Draft compilation as of 11_01_2024, 6789 barriers

Schoen, E.R., Howard, K.G., Murphy, J.M., Schindler, D.E., Westley, P.A. and von Biela, V.R., 2023. Divergent responses of western Alaska salmon to a changing climate. NOAA Technical Report OAR ARC, pp.23-33.

Seaber, P.R., Kapinos, F.P., and Knapp, G.L. 1987. Hydrologic Unit Maps: U.S. Geological Survey Water-Supply Paper 2294, 63 p.

Shanley, C.S. and Albert, D.M., 2014. Climate change sensitivity index for Pacific salmon habitat in Southeast Alaska. *PLoS One*, *9*(8), p.e104799.

Sidik, S. M. 2025. Alaska's lakes and ponds reveal effects of permafrost thaw, Eos, 106, https://doi.org/10.1029/2025EO250063. Published on 19 February 2025.

Sjöberg, Y., A. Jan, S. L. Painter, E. T. Coon, M. P. Carey, J. A. O'Donnell, and J. C. Koch. 2021. Permafrost promotes shallow groundwater flow and warmer headwater streams. Water Resources Research 57(2): e2020WR027463

Stein, B.A., and S.R. Flack. 1997. 1997 Species Report Card: The State of U.S. Plants and Animals. The Nature Conservancy, Arlington, Virginia. 26pp.

Stephenson, P. J. (2019). The Holy Grail of biodiversity conservation management: Monitoring impact in projects and project portfolios. Perspectives in Ecology and Conservation, 17(4), 182–192. https://doi.org/10.1016/j.pecon.2019.11.003

Tabari, H., 2020. Climate change impact on flood and extreme precipitation increases with water availability. Scientific reports, 10(1), p.13768.

Thornbrugh, D. J., Leibowitz, S. G., Hill, R. A., Weber, M. H., Olsen, A. R., & Kaufmann, P. R. (2018). The StreamCat Dataset: A national database of watershed metrics for stream and river management and research. Ecological Indicators, 85, 1030–1038. https://doi.org/10.1016/j.ecolind.2017.10.070

Timpane-Padgham, B.L., Beechie, T. and Klinger, T., 2017. A systematic review of ecological attributes that confer resilience to climate change in environmental restoration. *PLoS One*, *12*(3), p.e0173812.

Tickner, D., Opperman, J.J., Abell, R., Acreman, M., Arthington, A.H., Bunn, S.E., Cooke, S.J., Dalton, J., Darwall, W., Edwards, G., Harrison, I.A.N., Hughes, K., Jones, T.I.M., Leclère, D., Lynch, A.J., Leonard, P., Mcclain, M.E., Muruven, D., Olden, J.D., and Young,

L. 2020. Bending the curve of global freshwater biodiversity loss: an emergency recovery plan. BioScience, 70(4):330–342. https://doi.org/10.1093/biosci/biaa002

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

United Nations Environmental Programme (UNEP). 2022. Convention on Biodiversity, Kunming-Montreal Global Biodiversity Framework. https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf.

U.S. Army Corps of Engineers (USACE). National Inventory of Dams. Retrieved from https://nid.sec.usace.army.mil downloaded 4/15/2025

U.S. Census Bureau. 2024. TIGER/Line Shapefile, Alaska. All Roads and Railroads. Retrieved from https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.html

U.S. Geological Survey, National Geospatial Program. 2023 USGS National Hydrography Dataset Best Resolution (NHD) - Alaska (published 20231227) FileGDB Reston, VA. U.S. Geological Survey.

University of Alaska, Fairbanks, Geophysical Institute Permafrost Laboratory. 2011. GIPL1.3 simulated maximum active layer thickness (ALT) in meters averaged for particular decade for the entire Alaskan permafrost domain. Published by the Arctic Landscape Conservation Cooperative. 2km raster datasets. ALT_2040_2049.tif , ALT_2010_2019.tif Data produced by Dr. Sergei Marchenko, ssmarchenko@alaska.edu. Online_Linkage: http://arcticlcc.org/products/spatial-data/show/simulated-active-layer-thickness

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R. and E. Cushing. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences, 37:130-137.

Walvoord, M.A. and Kurylyk, B.L., 2016. Hydrologic impacts of thawing permafrost—A review. Vadose Zone Journal, 15(6), pp.vzj2016-01.

Wang, L., Infante, D., Esselman, P., Cooper, A., Wu, D., Taylor, W., Beard, D., Whelan, G. and Ostroff, A. 2011. A hierarchical spatial framework and database for the National River Fish Habitat Condition Assessment. Fisheries, 36(9):436-449, DOI: 10.1080/03632415.2011.607075.

Webb, E.E., Liljedahl, A.K., Cordeiro, J.A., Loranty, M.M., Witharana, C. and Lichstein, J.W., 2022. Permafrost thaw drives surface water decline across lake-rich regions of the Arctic. *Nature Climate Change*, *12*(9), pp.841-846.

Westley, Peter. 2023 Confirmed: Salmon are spawning in Arctic rivers Oct. 5, 2023

UAF news and information https://www.uaf.edu/news/confirmed-salmon-are-spawning-in-arctic-rivers.php

Whited, Diane, C., J. Kimball, J. Lucotch, N. Maumenee, H. Wu, S. Chilcote, and J. Stanford. 2012. A Riverscape Analysis Tool Developed to Assist Wild Salmon Conservation Across The North Pacific Rim. Fisheries Vol. 37. No. 7 p.305-314

Whitney, J. E., Al-Chokhachy, R., Bunnell, D. B., Caldwell, C. A., Cooke, S. J., Eliason, E. J., Rogers, M., Lynch, A. J., & Paukert, C. P. 2016. Physiological Basis of Climate Change Impacts on North American Inland Fishes. Fisheries, 41(7), 332–345. https://doi.org/10.1080/03632415.2016.1186656

Woodward, G., Perkins, D. M., & Brown, L. E. 2010. Climate change and freshwater ecosystems: Impacts across multiple levels of organization. Philosophical Transactions of the Royal Society B: Biological Sciences, 365(1549):2093–2106. https://doi.org/10.1098/rstb.2010.0055

World Wildlife Fund (WWF) and The Nature Conservancy (TNC). 2019. Freshwater Ecoregions of the World. feow.org

Yamazaki, D., Ikeshima, D., Sosa, J., Bates, P.D., Allen, G.H. and Pavelsky, T.M., 2019. MERIT Hydro: A high-resolution global hydrography map based on latest topography dataset. Water Resources Research, 55(6), pp.5053-5073. (downloaded 11/24/2024, https://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_Hydro/)

Zhang, Alice Tianbo, and Vincent Xinyi Gu. 2023. “Global Dam Tracker: A Database of More than 35,000 Dams with Location, Catchment, and Attribute Information.” Sci Data. (additional 8 dams)

Zomer, R.J., Xu, J. and Trabucco, A., 2022. Version 3 of the global aridity index and potential evapotranspiration database. *Scientific Data*, *9*(1), p.409.