

Rusting Rivers: Assessing the Causes and Consequences in Alaska and Across the Arctic

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Headlines

- In Arctic Alaska, surface waters have changed from clear to orange in over 200 watersheds, with most changes occurring within the past decade. Evidence suggests this "rusting" is an emerging issue due to iron release from thawing permafrost soils.
- Rusting rivers have degraded water quality and habitat, with increased acidity and toxic trace metal concentrations contributing to a loss of aquatic biodiversity in headwater streams.
- Ongoing research aims to understand the causes and consequences of rusting rivers, particularly regarding impacts to drinking water supplies for rural communities and subsistence fisheries.

Introduction

Terrestrial and aquatic ecosystems of the Arctic are undergoing rapid change due to the impacts of a changing climate and ecosystem disturbances. One climate-driven disturbance, permafrost thaw, is altering watershed hydrology and biogeochemical cycles (e.g., carbon cycling), with implications for coastal waters and marine ecosystems. Recent ground-based, aerial, and satellite observations from remote watersheds of northern Alaska indicate that hundreds of streams and rivers have shifted from pristine, clear water to an orange "rusting" condition, with many sites changing over the past decade (O'Donnell et al. 2024). This abrupt change appears to be an unanticipated consequence of permafrost thaw in the Arctic, and represents an emergent risk to water quality and aquatic life (Miner et al. 2021).

The leading hypothesis describing this recent phenomenon is that permafrost thaw is exposing previously inaccessible mineral deposits, such as sulfide minerals (e.g., pyrite), to chemical weathering. These abiotic processes in the subsurface generate acid, sulfate, and metals that are transported by groundwater flow to stream ecosystems. Rusting rivers indicate the presence of oxidized iron particles, but laboratory analyses indicate that orange-colored streams also have elevated concentrations of toxic trace metals like copper, aluminum, and zinc. In this essay, we discuss the spatial and temporal patterns of rusting rivers, the broader historical context of permafrost thaw and weathering processes, and the implications for water quality and fisheries across the Circum-Arctic region.

Occurrence and causes of rusting rivers

In a 2024 study, we reported on the emergence of 75 streams in Alaska's Brooks Range that had turned from clear to orange (O'Donnell et al. 2024). Since then, we have compiled additional observations from more than 200 streams and rivers that are discolored (Fig. 1; Hill 2024). These rusting rivers are visually striking (Fig. 2a,c,e) and are readily detected using satellite imagery. Using historical satellite imagery, we showed that most of these streams have changed color in the past 10 years. This shift coincides with a dramatic increase in air and ground temperatures across the region, indicating that recent permafrost thaw is a likely driver (Swanson et al. 2021).

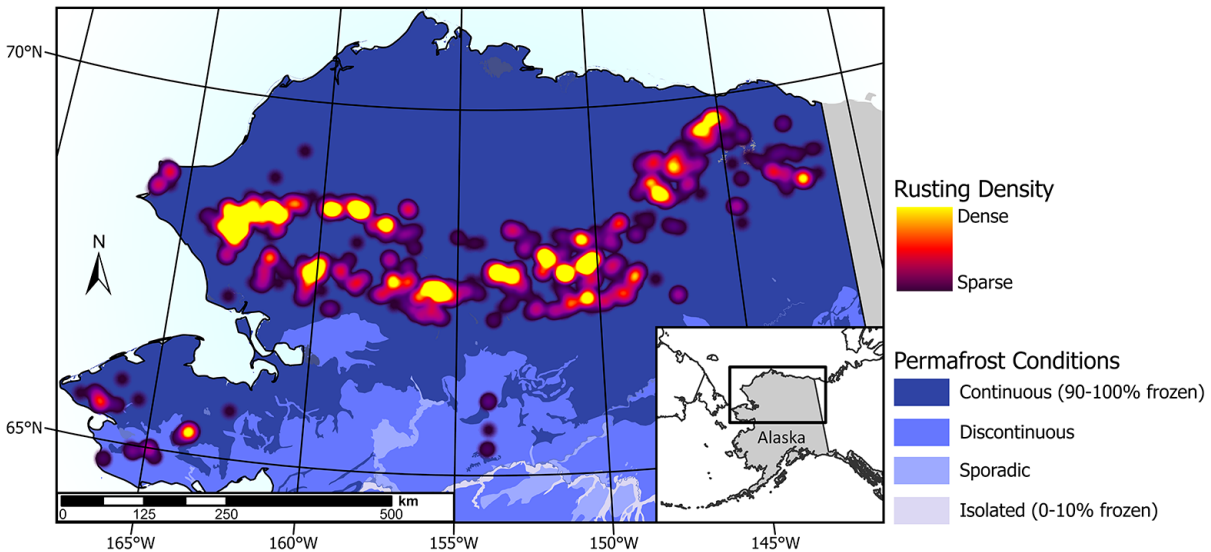


Fig. 1. Heat map depicting density of rusting rivers in northern Alaska based on in situ and satellite observations from 2007-24. The base map depicts permafrost zones as classified by Jorgenson et al. (2008).

A more in-depth analysis of a U.S. Geological Survey (USGS) Landsat satellite time series for a subset of streams indicated that (1) rusting initiated around 2018 and has continued, and (2) some streams had prior periods of rusting and recovered to clear-water conditions (Fig. 2b,d,f). It is currently unknown what drives interannual and seasonal patterns of stream discoloration. The winter of 2017/18 was also a year of deep snowpack (Mudryk et al. 2018; see essay [Snow Cover](#)), which can accelerate thaw. Further, seasonal variation in stream flow can influence stream color, with high flow conditions diluting the appearance of iron oxides. There are certainly rusting rivers that precede this recent period of warming. However, the abrupt increase in the number of rusting rivers and the broad spatial extent of these observations (more than 1000 km west to east) suggest regional climate drivers and soil thaw are likely to have caused the emergence of these discolored waters.

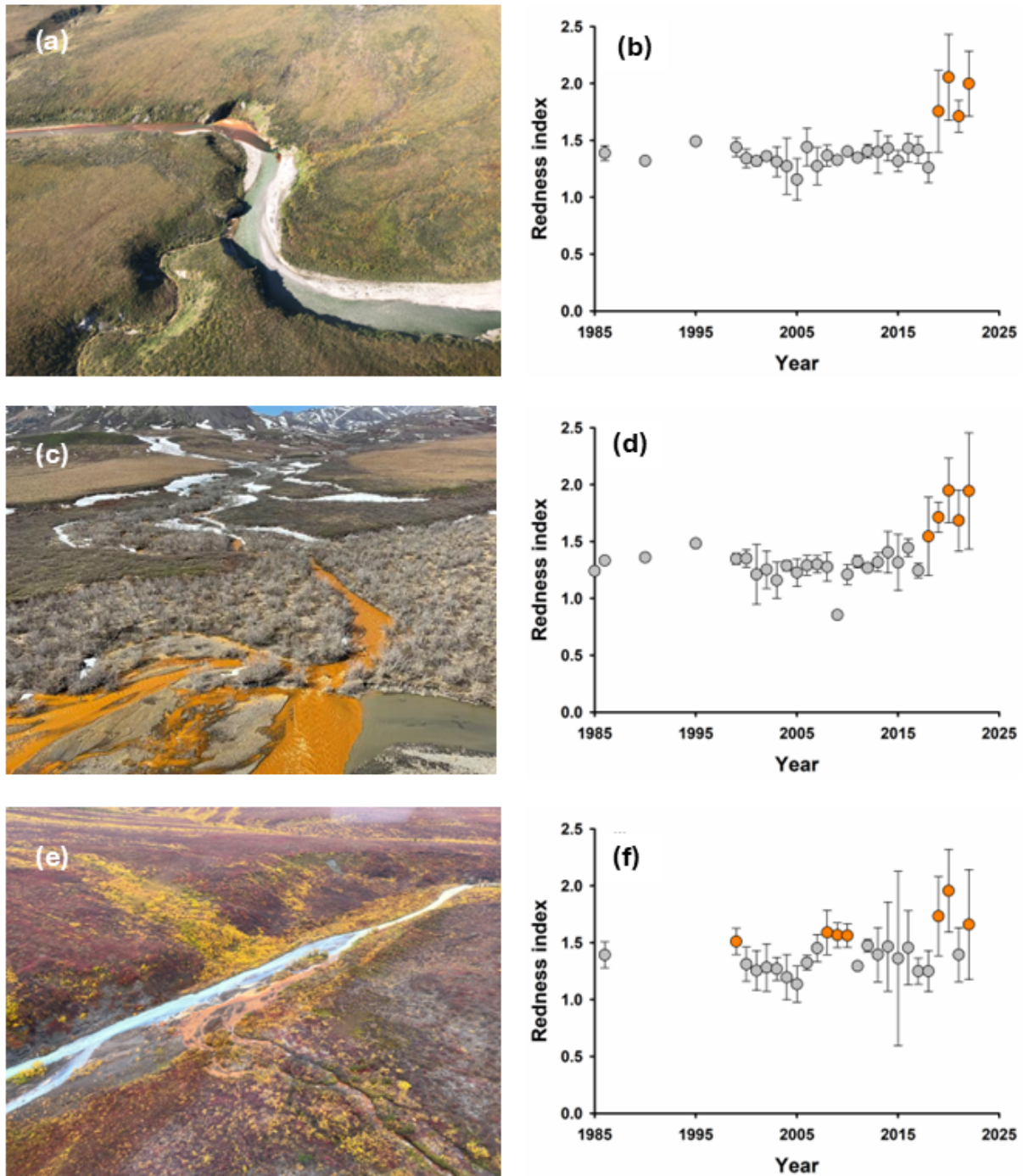


Fig. 2. Photographs of rusting rivers and time series plots of Redness Index for watersheds in Alaska's Brooks Range, including the Agashashok River (Noatak National Preserve, panels a, b), the Kuguruk River (Noatak National Preserve, panels c, d), and Anaktok Creek, a tributary of the Salmon Wild and Scenic River in Kobuk Valley National Park (panels e, f). The time-series data were generated from Landsat satellite images using average Redness Index values for summer months of each year from 1985 through 2022. Redness index, which represents the presence of iron oxides, was calculated as the ratio of surface reflectance of the red and blue bands. The orange circles with mean ($\pm$ standard deviation) Redness Index values > 1.5 indicate waters discolored by iron particles. Grey circles represent mean Redness Index values < 1.5, indicating clear water or streams unimpacted by iron mobilization. Photo credits: Jonathan O'Donnell/NPS, Michael Carey/USGS, and Joshua Koch/USGS.

Much of the rusting we observed was due to acid rock drainage—chemical weathering that releases iron, acid, sulfate, and trace metals (e.g., copper, zinc, and others) into surface waters (Fig. 3). Rusting rivers are common in the continuous permafrost zone (Fig. 1) and in alpine and rocky watersheds of the Brooks Range where sulfide minerals like pyrite are present. Acid rock drainage waters often emerge via groundwater seeps that develop on terrestrial hillslopes and drain into streams and rivers. As the climate warms and permafrost thaws, groundwater can be rerouted to deep soil layers where it can drive chemical weathering reactions and the mobilization of acid and toxic metals (Fig. 4). Widespread talik formation (i.e., the development of year-round unfrozen layers in permafrost soils) may be an important contributor to this phenomenon (Farquharson et al. 2022). While acid rock drainage appears to be the dominant process contributing to stream impairment, rusting rivers can also be caused by microbial mobilization of soil iron stocks in response to permafrost thaw, shifting soil drainage, and changing redox conditions (Barker et al. 2023; Fig. 4). This microbial pathway can cause streams to turn orange from iron particulates, but these streams do not have elevated toxic metal concentrations as in the case of acid rock drainage.

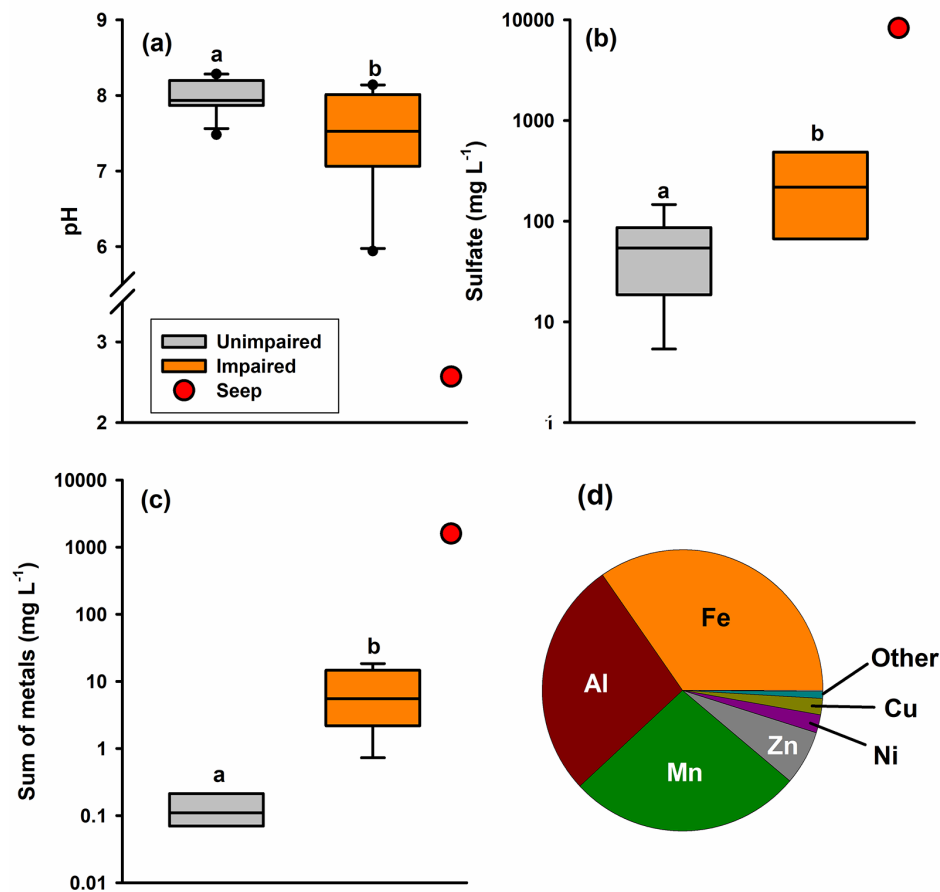


Fig. 3. Summary of geochemical observations from impaired rusting rivers, unimpaired reference sites, and impaired groundwater seeps. (a) Impaired sites and groundwater seeps are more acidic (i.e., have low pH) than unimpaired clearwater sites. (b) Impaired sites and seeps have higher sulfate concentrations than unimpaired sites, indicating the chemical weathering of sulfide minerals (e.g., pyrite). (c) The sum of total metals is higher in impaired sites and seeps than in unimpaired sites. Note: panels (b) and (c) are plotted in log scale. (d) The pie chart presents the average distribution of metals from impaired, rusting rivers. Major metals like iron (Fe), aluminum (Al), and manganese (Mn) dominate. However, concentrations of toxic travel metals, such as zinc (Zn), nickel (Ni), copper (Cu), and others, are also present at high concentrations.

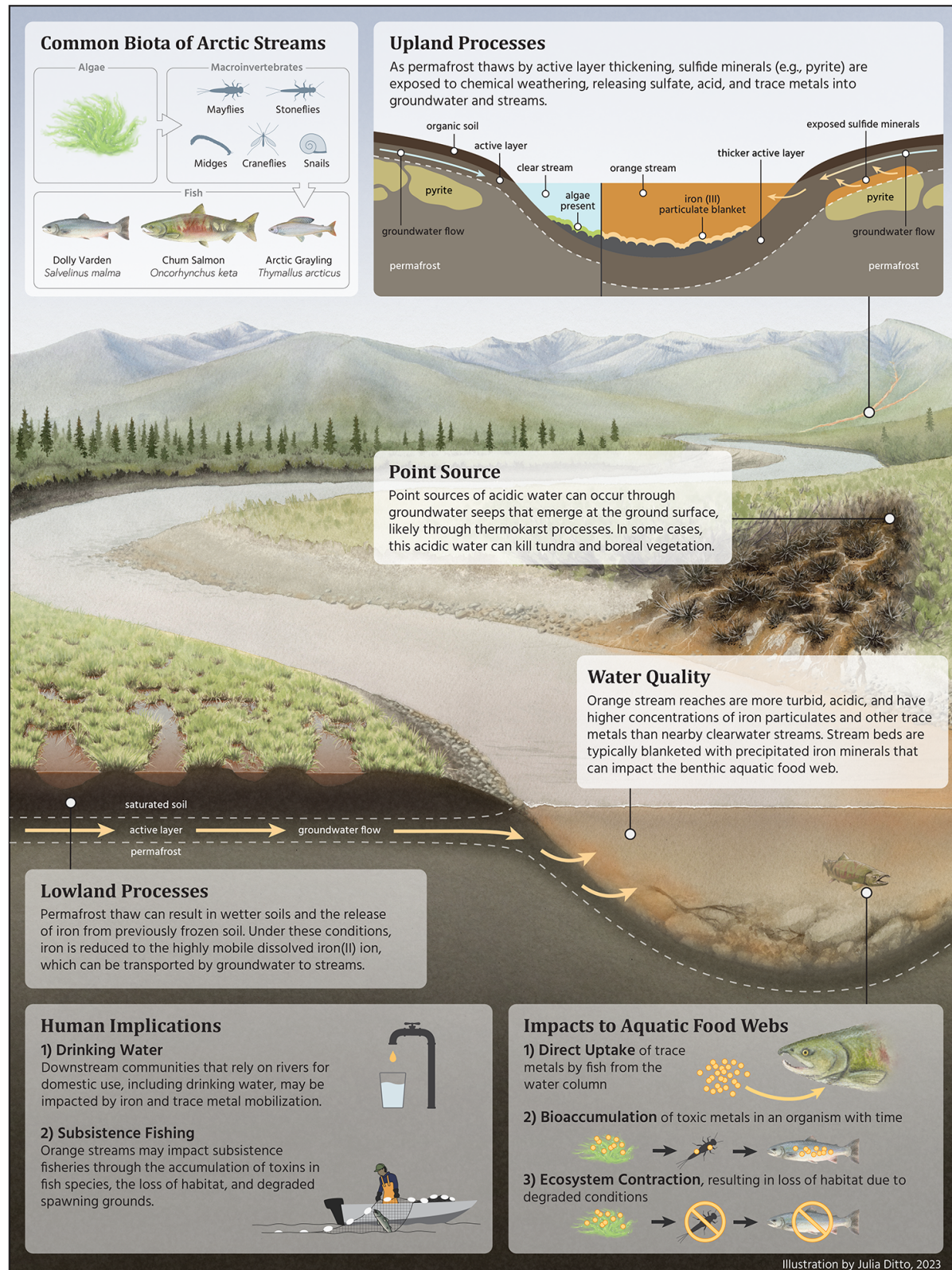


Fig. 4. Conceptual illustrations of hypothesized processes contributing to rusting rivers in northern Alaska and their impacts. Illustration by Julia Ditto, 2023

Observations of iron mobilization from Alaska's North Slope and in peatlands of northern Sweden are likely due to microbial mobilization of iron, not acid rock drainage, in part due to their topographic setting in lowland tundra (Barker et al. 2023; Patzner et al. 2020). Depending on the setting, these lowland rusting rivers could have occurred throughout recent history during periods of soil wetting and drying, and in the absence of permafrost thaw. Whatever mechanisms may be occurring, the increased flux of iron from rivers to the coast could increase marine primary productivity, which is limited in part by iron availability (see essay [Primary Productivity](#)).

Why river rusting matters

Arctic rivers provide habitat for a broad array of fish, many of which are critical for subsistence, sport, and commercial fisheries. Climate change is already impacting high-latitude fish species, including Pacific salmon (*Oncorhynchus* spp.), due to effects of warming on marine and freshwater ecosystems (see essay [Warming Waters and Borealization](#)). Adding to those concerns, mobilization of iron and toxic metals to Arctic streams in northern Alaska may degrade water quality, reduce habitat, and bioaccumulate in aquatic food webs.

Within Kobuk Valley National Park, we observed a sharp decrease in stream biodiversity at an existing monitoring location when a headwater tributary of the Akillik River changed from clear to orange between early and late summer of the same year (O'Donnell et al. 2024). We documented the complete loss of fish species, juvenile Dolly Varden (*Salvelinus malma*) and Slimy Sculpin (*Cottus cognatus*), after an abrupt increase in stream acidity. The loss of fish coincided with a steep decrease in benthic (bottom dwelling) macroinvertebrate diversity and algal biomass on the stream bed. While the underlying causes for this decline in biodiversity are unknown, evidence from the Salmon Wild and Scenic River in Kobuk Valley National Park indicates that many rusting rivers exceed chronic metal exposure criteria established by the U.S. Environmental Protection Agency (EPA; Sullivan et al. 2025).

Beyond the effects on fish, rusting rivers may impact drinking water supplies to rural communities. Some metals, such as cadmium, nickel, and manganese, exceeded either EPA drinking water criteria or World Health Organization guidelines in orange-colored streams (O'Donnell et al. 2024). At a minimum, this disturbance may present taste issues for drinking water that require enhanced water filtration to mitigate the increase in metals. In rural Alaska, climate and permafrost thaw present direct threats to water resources. Disturbance along river corridors, including bank erosion and retrogressive thaw slumps (i.e., landslides caused by thawing permafrost soils), can profoundly affect water quality through deposition of sediments, nutrients, and ions in river water. The observed presence of dissolved and particulate metals through processes described here present a similar challenge to drinking water access in remote Alaska, particularly for villages near rusting rivers.

These findings of water quality degradation in northern Alaska clarify broader implications for the Circum-Arctic region and waters draining landscapes undergoing permafrost thaw and deglaciation (see essay [Glaciers and Ice Caps](#)). Recent work has documented the relationship between permafrost thaw and sulfide chemical weathering in the Yukon and Mackenzie rivers in western Canada and Alaska (Kemeny et al. 2023). Another recent review highlighted concerns for water quality across the northern permafrost region due to these underlying processes (Skierszkan et al. 2024). Other studies have documented rusting and metal mobilization in watersheds undergoing mountain permafrost thaw or glacier melt, as in temperate regions of the Alps and tropical regions of Peru (Santofimia et al. 2017; Wanner et al. 2023). These global observations point toward the broader loss of the cryosphere as an

issue driving water quality impairment. Additional research could help better understand the causes and consequences of this emerging environmental issue.

Methods and data

Detailed field, remote sensing, and analytical methods can be found in O'Donnell et al. (2024). USGS and the National Park Service have published data releases for observations of rusting rivers (Hill 2024), stream and river chemistry (Koch et al. 2023), and aquatic biota (Carey et al. 2023). Additional photographs of rusting rivers are hosted by the [USGS](#). A [five-minute](#) video documenting rusting rivers was produced by the University of California Davis and can be accessed via YouTube. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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