

Metal Mobilization from Thawing Permafrost Is an Emergent Risk to Water Resources

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ABSTRACT: Metals are ubiquitous in Earth's Critical Zone and play key roles in ecosystem function, human health, and water security. They are essential nutrients at low concentrations, yet some metals are toxic at a high dose. Permafrost thaw substantially alters all the physical and chemical processes governing metal mobility, including water movement and solute transport and (bio)geochemical interactions involving water, organic matter, minerals, and microbes. The outcomes of these interconnected changes are nonintuitive yet hold global implications for water resources and ecosystem health. This Perspective outlines the primary factors affecting metal mobility in thawing permafrost and underscores the urgent need and priorities for interdisciplinary research to better understand this emerging issue.



1. INTRODUCTION

Permafrost underlies ~15% of land in the Northern Hemisphere and is also prevalent in mountainous regions globally, covering an area larger than Canada (Figure 1).^{1,2} Water entrapped within permafrost accounts for a greater share of global freshwater than all of Earth's lakes and rivers combined.³ This reservoir of frozen ground is currently thawing faster than at any time since the start of the Holocene epoch (11,700 years ago) because of global warming.⁴ Arctic temperatures have risen +1.25 °C decade⁻¹ in the last 50 years,⁵ with projected increases of 3 to 13 °C by the year 2100.⁶ The Arctic has also warmed faster in the last 50 years than during any other period in the last two millennia and is warming faster than the global average.⁷ As a result, the global permafrost extent is projected to decrease by 5–20% within the next generation's lifetime.⁷

Permafrost thaw imposes drastic changes in water movement and chemistry in cold regions. The transition from frozen to unfrozen conditions increases ground hydraulic conductivity by orders of magnitude as ice-filled pores thaw.⁸ This shift enhances infiltration of meteoric waters and intensifies groundwater circulation and its interaction with surface water.^{9–12} Ground thawing also promotes physical and chemical interactions between water, minerals, organic matter, and microbes. In its frozen state, water's ability to interact chemically with its surroundings is limited, whereas liquid water is a formidable solvent driving biogeochemical processes that govern aqueous chemistry.¹³ The consequence of these changes is a dramatic shift in all of the environmental variables governing the fate of metals: water residence time; mineral-water-organic matter interactions; microbial and geochemical reactions; and aqueous geochemistry (pH, redox, major-ion concentrations, organic matter properties and abundance).

Collectively, these changes intensify water–solid interaction and (bio)geochemical cycling, with global implications for water chemistry, quality, and security.^{11,14}

While the hydrological,^{15,16} hydrogeological,^{9,11} and microbiological^{17,18} implications of thawing permafrost have gained increasing attention in recent years, consequences for the fate of metals in the environment remain poorly understood. Metals, which we define broadly here to include metals and metalloids, are essential for life on Earth as they serve key metabolic functions.¹⁹ They are ubiquitous, typically found at trace (parts per million or less) levels in soil, rock, and water, yet can be toxic at elevated dose. Certain naturally occurring metals have radioactive isotopes (e.g., potassium, radium, polonium, lead, uranium, and thorium). The significance of geogenic and anthropogenic metals as global nutrients and toxicants and their role in ecosystem and human health makes it critical to understand their global (bio)geochemical cycling.

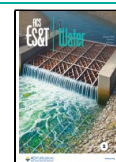
Recent studies have underscored emerging risks associated with anthropogenic metals in thawing permafrost landscapes,^{18,20} yet geogenic metals have received comparably less attention. Nevertheless, the scientific literature addressing metal (bio)geochemistry in permafrost regions has grown exponentially in recent years (Figure 2) and demonstrates evidence of intensified metal mobilization.^{21–24} Key processes

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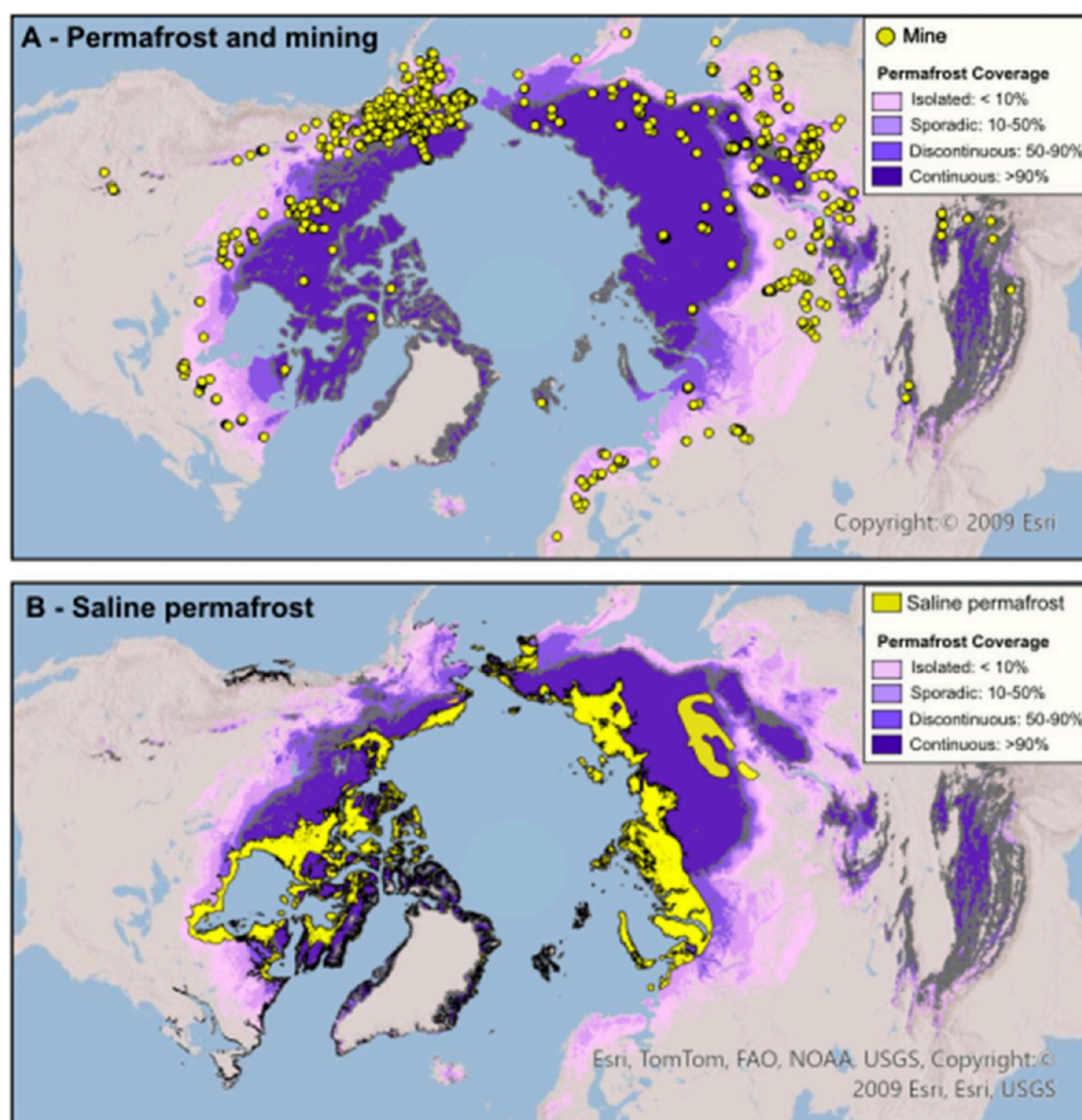


Figure 1. (A, B) Maps of Northern Hemisphere permafrost, mines in the permafrost zone, and saline permafrost. Permafrost distribution is from Obu et al.¹ Mine sites are taken from Maus et al.'s international compilation, the US Geological Survey, the Northwest Territory Geological Survey, and the Yukon Geological Survey and clipped to Obu et al.'s permafrost zonation.^{32–35} Saline permafrost map compiled from Jones et al.,³¹ Dyke et al.,³⁶ and Cherniak et al.³⁷

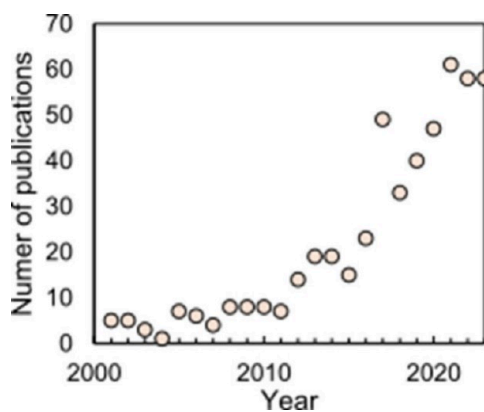


Figure 2. Yearly publication output under the topic “permafrost metal*” for the years 2000–2023 reported by a Web of Science search (2024-08-15).

include increases in (1) sulfide mineral oxidation and acid-rock drainage that mobilizes iron, aluminum and cation-forming metals such as nickel and zinc;^{22,25–27} (2) redox cycling in the active layer that mobilizes metals soluble under reducing conditions such as iron, manganese, and arsenic; (3) (bio)geochemical cycling of metals complexed by organic matter such as iron, aluminum, lead, mercury, selenium, and uranium;^{28–30} and (4) hydrological cycling of saline fluids characteristic of the cryosphere.³¹

This Perspective presents an overview of the key (bio)-geochemical controls on metal mobility in thawing permafrost regions, drawing on recent literature. We identify research priorities essential to better understand metal mobilization and manage water security during rapid global warming. We hope to raise awareness of this emergent and societally relevant phenomenon and stimulate further research to better understand it.

2. TEMPERATURE AS A KEY CONTROL IN (BIO)GEOCHEMICAL REACTIONS INVOLVING METALS

We have already stated the critical importance of the physical state of water (liquid vs solid) as a pivotal control on (bio)geochemical reactions. In addition, the temperature plays a key role in microbial and geochemical reaction kinetics and thermodynamics. Most geochemical reactions controlling metal mobility on Earth are rate-limited, including mineral dissolution—precipitation, oxidation—reduction, and respiration.^{38,39} Fundamental chemical and biological principles demonstrate that reaction rates increase exponentially with temperature.^{40,41} For example, uranium can be immobilized through microbially mediated reduction at temperatures relevant to the active layer, while these microbial processes are ineffective at colder temperatures characteristic of permafrost.⁴² Sulfide-mineral oxidation kinetics are also temperature-dependent, leading to coupling between warming temperatures, permafrost thaw, and sulfate export in northern rivers.⁴³ The balance between products and reactants in (bio)geochemical reactions operating at thermodynamic equilibrium also depends on temperature.⁴⁴ It follows that permafrost thaw enhances the (bio)geochemical reaction potential when water changes from a predominantly solid to a liquid state, and that progressive warming further induces fundamental changes in (bio)geochemical reactions governing metal mobility. Melt-freeze cycling introduces additional complexities governing metal mobility that are characteristic of cold climates. Solute exclusion and partial melt introduce poorly understood chemical differentiations in cryotic fluids that can promote precipitation-dissolution and sorption-desorption reactions capable of immobilizing or mobilizing metals.^{45,46}

3. CHANGING WATER FLOWPATHS RESULTING FROM GROUND THAW ALTER METAL EXPORT REGIMES FROM GROUNDWATER TO SURFACE WATER

Permafrost catchments have seasonally variable chemical and physical hydrology influenced by the frozen ground that segregates shallow and deep flowpaths.⁸ In most hydrogeologic systems water chemistry evolves with depth because surficial acidity from biogenic CO₂ and organic acids is buffered by mineral dissolution,⁴⁷ and limited atmospheric exchange below the water table promotes chemically reducing conditions in deep groundwater.⁴⁸ These depth-dependent pH and redox conditions translate to differential transport processes of metals in the subsurface based on their distinct geochemical properties.¹⁴ By degrading the permafrost barrier that separates shallow and deep flow systems, thawing can substantially alter metal transport pathways from groundwater to surface water. Additionally, chemical distinctions between shallow and deep groundwater flowpaths drive geochemical reactions in areas of flowpath convergence such as the hyporheic zone.^{10,14,49,50}

Increased groundwater discharge as permafrost thaws may favor export of groundwater-associated metals to surface waters, such as oxyanion-forming elements antimony, arsenic, chromium, molybdenum, selenium, and uranium.^{14,51,52} Peak concentrations of these metals in surface water of permafrost regions have been observed during periods of low flow, particularly during winter when deeper flowpaths sustain surface water baseflows and provide critical overwintering

habitat for aquatic organisms.^{15,53} Conversely, spring floods involve maximal contributions of shallower and more acidic flowpaths⁵⁴ due to frozen soil conditions and transport of colloidal and suspended metal-bearing particles.^{14,15} These floods are associated with peak discharge of particle-bound iron, copper, nickel, lead, and mercury.^{14,49,50,55} Active-layer expansion during summer thaw releases metal cations (e.g., aluminum, cobalt, cadmium, copper, iron, manganese, nickel, lead, titanium, vanadium, and zinc) that are mobile under the reducing and slightly acidic conditions of organic-rich soils.^{14,21,52} Overall, progressively deeper water flowpaths resulting from thawing permafrost therefore alter seasonal metal concentrations and export processes in surface water bodies, yet uncertainties remain regarding metal transport processes and (bio)geochemical reactions during mixing of chemically distinct flowpaths in thawing permafrost catchments. These uncertainties hold substantial implications for aquatic ecosystems where metals can be growth-limiting micronutrients⁵⁶ and/or toxicants.

4. (BIO)GEOCHEMICAL DRIVERS OF METAL MOBILIZATION DURING PERMAFROST THAW

As of this writing, detailed studies on a selection of metals (arsenic, iron, lead, manganese, mercury, selenium, and uranium) shed light on their speciation in permafrost and identify key (bio)geochemical reactions controlling their fate during permafrost thaw.^{23,24,29,30,49,57–60} While different metals have distinct geochemical properties, common processes controlling their mobility include activation of flowpaths previously occluded by freezing; onset of redox reactions triggered by enhanced microbial activity; physical transport of reactive reductants (e.g., organic matter) and oxidants (e.g., atmospheric oxygen) into the newly thawed subsurface; changes in water pH; and metal interactions with inorganic and organic ligands.

4.1. Metals Mobilized in Conjunction with (Bio)-geochemical Cycling of Organic Matter. Mercury is perhaps the best-studied trace metal in a permafrost context, owing to its high toxicity and its circumpolar enrichment by northward deposition of atmospheric mercury.⁶¹ Mercury deposited in northern latitudes over the Holocene epoch has been trapped by organic matter, buried through sedimentation, and preserved by aggrading permafrost.⁶¹ As a result, more mercury is found in permafrost soils than the global atmosphere, oceans, and soils combined.^{61,62} As permafrost thaws, this mercury is repartitioned through active biogeochemical cycling and water bodies.⁶³ Its fate is directly linked to organic-matter cycling, because of its strong chemical affinity toward organic ligands.⁶⁴ The water-saturated environments rich in labile organic matter that characterize low-lying thermokarst landscapes favor anaerobic heterotrophic microbes such as iron reducers, sulfate reducers, and methanogens that are capable of methylating mercury.^{65–68} The high toxicity of methyl-mercury exacerbates risks associated with microbial mercury cycling during permafrost thaw. Additional pathways of mercury release from thawing permafrost include erosion of particle-bound mercury from permafrost thaw slumps, and export of aqueous mercury(II) complexes and methylmercury along groundwater flow systems.^{58,63,69} The cumulative consequence of these changes has been mercury bioaccumulation in food webs to unsafe levels, which is particularly problematic in northern communities with a high reliance on local wild foods.⁷⁰

Elsewhere, visually striking “rusting” of Arctic waterbodies highlights enhanced export of iron and other metals previously stored in permafrost to aquatic ecosystems (Figure 3).^{22,71}



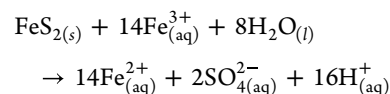
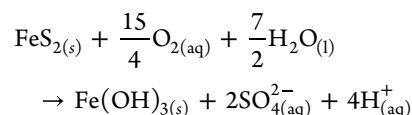
Figure 3. Examples of iron mobilization in permafrost regions. (A) Iron-(oxyhydr)oxide export from Slavin Creek, Tombstone Waters Observatory, Yukon during snowmelt (Photo credit: Arsh Grewal, McMaster University). (B) Iron export in Engineer Creek, Yukon, driven by sulfide-mineral oxidation (Photo credit: Elliott Skierszkan, Carleton University).

These orange-stained streams can result from redox-driven iron mobilization, and increased rates of sulfide-mineral oxidation and acid-rock drainage (further discussed under section 4.2).^{22,24} Biodegradation of labile permafrost organic matter favors anaerobic conditions in the active layer, particularly in low-lying areas where water saturation occurs due to the low hydraulic conductivity of underlying permafrost.^{72–74} Active-layer anoxia drives important changes in the mobility of redox-sensitive metals, most notably by triggering reductive dissolution of iron(III)-(oxyhydr)oxides and manganese(IV) oxides via heterotrophic anaerobic respiration pathways.^{24,59,74–76} These pathways are supported by elevated heterotrophic anaerobic microbial populations in the active layer⁷⁷ and can favor release of toxic metals sorbed onto iron and manganese (oxyhydr)oxides such as arsenic (Figure 4).²³ Iron, manganese, and arsenic are mobile under circumneutral-pH and anoxic conditions, facilitating their export from the active layer to oxic surface waters. Here, iron(II) oxidation precipitates ochreous iron(III) (oxyhydr)-oxide that can bind arsenic.^{23,24} Ecological impacts of iron mobilization are variable. Excessive iron exposure is toxic and extensive iron(III) (oxyhydr)oxide coating of stream beds can destroy benthic habitats,⁷⁸ yet iron also acts as the growth-limiting micronutrient in one-third of Earth's oceans.⁷⁹ Arsenic has no known biological function in humans, and its mobilization during reductive dissolution of iron (oxyhydr)-oxides has recently been associated with thawing permafrost.²³

Similar redox-driven processes associated with active-layer expansion, organic matter degradation, and/or rising water tables likely enhances leaching of other metals that are mobile under reducing conditions (e.g., vanadium, antimony), while sequestering those which are not (e.g., selenium, chromium).²⁹

Liberation of previously frozen organic matter is also directly implicated in metal mobilization due to its abundance in cryosols and its strong metal-chelating properties. This affinity has enriched organic-rich permafrost soils in uranium relative to surrounding media by stripping it from infiltrating groundwater over geologic time (Figure 4).³⁰ During permafrost thaw, enhanced biogeochemical cycling of dissolved organic matter can remobilize this uranium to porewater as uranium-organic carbon complexes.^{30,80} Although reducing conditions can favor uranium sequestration as immobile uranium(IV) phases, permafrost uranium appears to be dominated by its mobile hexavalent state, possibly because of uranium(VI) stabilization by organic matter and/or limitations on uranium(VI) reduction kinetics because of cold temperatures.^{30,42,81} Organic matter can also mobilize other elements including aluminum, cobalt, cadmium, copper, iron, lead, selenium, rare-earth elements, titanium) as colloidal and dissolved complexes in thawing permafrost landscapes (Figure 4 and Figure 5).^{29,82} However, the fate of redox-sensitive metals in organic-rich soils is complex, because in their most reduced oxidation states some metals are poorly mobile [e.g., arsenic(–I),⁸³ uranium(IV), and selenium(0)].^{29,84–87} Molecular associations between metals and organic matter and changes in the oxidation state of redox-sensitive metals occurring during permafrost thaw remain poorly understood, although the available literature suggests organic matter cycling is of critical importance toward understanding metal release and attenuation after thaw.

4.2. Enhanced Sulfide-Mineral Oxidation and Acid-Rock Drainage. Permafrost thaw can expose metalliferous sulfide minerals to enhanced oxidative weathering and drive onset of acid-rock drainage (ARD, Figure 6).^{22,27,88} Sulfide-mineral oxidation is a globally significant source of metal mobilization that involves exposure of sulfide minerals to oxygen and liquid water and generates acidity, heat, and metals.^{89,90} Microbially mediated sulfide-mineral oxidation has been linked with ARD in multiple permafrost settings globally.^{91–96} A common driver of ARD is the oxidation of iron and sulfur in pyrite (FeS₂), a ubiquitous mineral in many sedimentary, igneous, and metamorphic rocks, which liberates 4 to 16 mol of H⁺ per mol of pyrite, depending on the reaction pathway:



Sulfide minerals commonly host various metals which can be mobilized by oxidative weathering, including arsenic, cadmium, copper, lead, molybdenum, nickel, selenium, and zinc.⁹⁰ Acid generated by sulfide mineral oxidation in turn accelerates weathering of carbonate and silicate minerals, further amplifying metal mobility.⁹⁰ When pH buffering from mineral weathering is outpaced by acid generation, extremely low pH

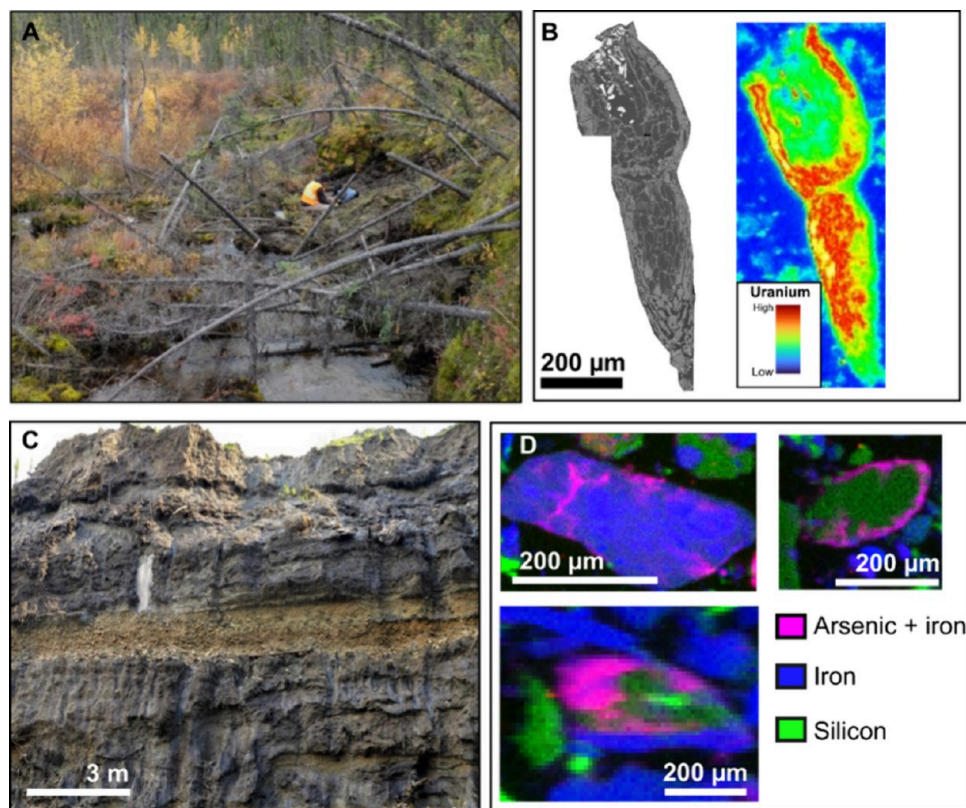


Figure 4. Examples of the involvement of organic matter in permafrost metal mobilization. Top: A permafrost thaw slump (A) mobilizing uranium associated with organic detritus (B) into a stream in the Dawson Range, Yukon, Canada. Panel B shows scanning-electron microscopy and micro X-ray fluorescence spectroscopy of uranium-bearing organic particles in permafrost soil, which contains up to $1,000 \mu\text{g g}^{-1}$ uranium in this area, while streamwater contains up to $340 \mu\text{g L}^{-1}$ uranium.³⁰ Bottom: A permafrost exposure in the Dawson Range shows coarse-grained and oxidized alluvium encapsulated in organic-rich soil (C). Thaw of this material activates carbon biodegradation and mobilizes arsenic, which occurs as reactive arsenic-bearing iron (oxyhydr)oxides visible in microscale X-ray fluorescence images (D). Photos were provided by Elliott Skierszkan, Carleton University. Adapted with permission from Skierszkan et al.^{23,30} © 2024, American Chemical Society.

(e.g. $\text{pH} < 3$) drives extreme metal concentrations (e.g., mg/L levels) under ARD conditions. Even under circumneutral pH conditions, sulfide-mineral oxidation can generate poor water quality by mobilizing metals that form oxyanions (e.g., antimony, arsenic, molybdenum, selenium, and uranium) or that are weak hydrolyzers (e.g., nickel, zinc).^{97,98}

Rising multidecadal sulfate fluxes in Arctic rivers point to largescale increases in sulfide-mineral oxidation,^{10,26,43} and the localized thaw-induced onset of ARD has been increasingly observed in headwater streams in permafrost regions in Yukon, Alaska, and mountainous regions of Europe and the continental USA.^{22,27,88,96,99} Permafrost thaw may enhance sulfide-mineral oxidation through a variety of mechanisms.¹⁰⁰ Warming temperatures increase iron and sulfur oxidation rates.^{93,100,101} Sulfide minerals previously occluded from flow systems by ice saturation of pores are subject to infiltration by liquid water after thaw;^{27,88} if this infiltration water contains sufficient oxidants [e.g., O_2 , iron(III)], sulfide-mineral oxidation ensues. Porewater cryoconcentration enhances sulfide-mineral oxidation by amplifying proton and iron(III) geochemical activity at the sulfide mineral-water interface,¹⁰² and by forming an electrolytic solution capable of bridging electron transfer between aqueous oxidants and sulfide minerals.¹⁰³ Sulfide-mineral oxidation may also be promoted where thermokarst erosion exposes sulfide minerals to oxygen, for example permafrost thaw slumps and melt/freeze-induced rock fracturing.^{96,100} The worst water quality in a study of

natural ARD in Yukon's continuous permafrost zone was observed in seepage from the base of a thaw slump, where pH 3.0 water contained 2.1 g L^{-1} sulfate, 150 mg L^{-1} zinc, 39 mg L^{-1} nickel, 2.9 mg L^{-1} copper, and 9.1 mg L^{-1} arsenic—the latter value exceeding Canada's aquatic-life water guidelines by a factor of 1820.⁹⁶ Sulfide-mineral oxidation is exothermic, and heat released by this reaction could create a positive feedback cycle between oxidation and permafrost thaw.¹⁰⁴ The high latent heat of ice (334 kJ kg^{-1}) relative to heat released by sulfide-mineral oxidation (e.g., for pyrite 0.012 kJ kg^{-1}) probably restricts this feedback cycle to sulfide-rich and ice-poor permafrost.^{100,104} Emergent evidence of ARD in permafrost catchments suggests that this phenomenon is an increasingly important driver of water quality in warming sulfide-rich geological terranes.

4.3. Sulfide-Mineral Oxidation and Mine-Waste Management. Surging global demand for critical minerals increases economic incentives to mine ore deposits in remote permafrost terrains.¹⁰⁵ The surface area impacted by mining within Northern Hemisphere permafrost is $\sim 4,700 \text{ km}^2$ (Figure 1).^{1,35} Alaska and Yukon alone host $>5,000$ known mineral deposits and $\sim 4,000$ current and past producers.^{106,107} Ore deposits are commonly associated with sulfide minerals, and mining operations can expose sulfide minerals to enhanced oxidative weathering, generating poor water quality that requires treatment prior to discharge to downgradient environments.¹⁰⁸ Release of sulfate, acidity, and metals from

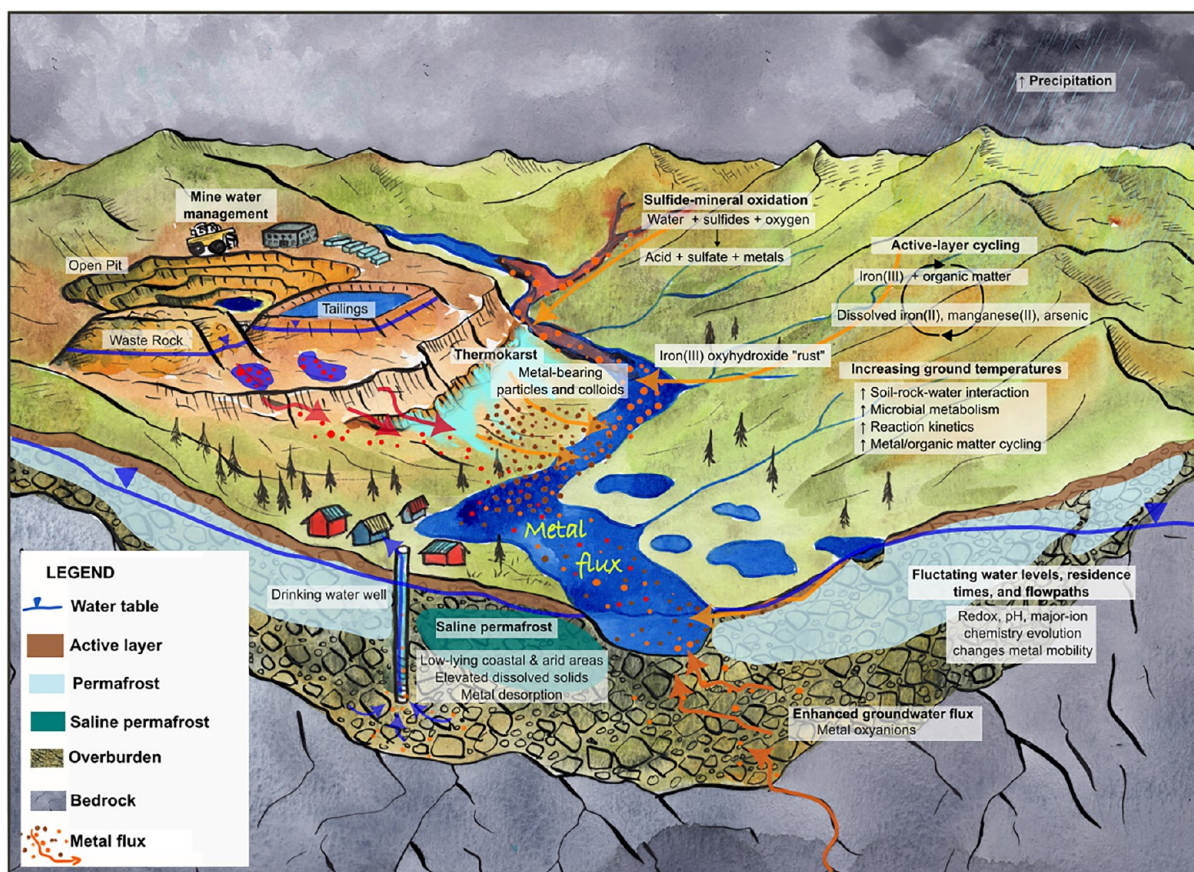


Figure 5. Conceptualization of dominant hydrogeological and geochemical processes operating on metals in permafrost landscapes. Colored arrows represent possible transport pathways for metal mobilization driven by thaw.

mine waste stockpiles can persist for millennia,⁸⁹ thus extending beyond the lifespan of modern mine operations and into future warmer climatic conditions. Unexpected deterioration in water quality because of intensified weathering of sulfide minerals and thaw-driven evolution in hydrogeological flowpaths presents a substantial liability for mine-site management under a warming climate. For example, the Red Dog zinc mine in Alaska was recently required at great cost (\$20 M CAD) to divert treated wastewater to its main pit to remain compliant with its discharge permit after thawing permafrost released naturally occurring metals to downgradient stream.¹⁰⁹ This example highlights challenges associated with mine-site management in sulfidic orebodies in the face of thawing permafrost.

4.4. Saline Permafrost and Metal Mobilization. Saline permafrost overlies over a third of the continuous permafrost zone, predominantly within coastal and arid Arctic regions.³¹ It is found across circumpolar regions including northern Canada,¹¹⁰ Siberia,¹¹¹ Svalbard,¹¹² and the Fennoscandian shield. Saline permafrost features continental and marine origins.¹¹¹ Continental saline permafrost forms via evaporative solute concentration under arid conditions prior to freezing. Marine saline permafrost formed during marine transgressions such as those that followed Pleistocene glaciations, after which global sea-level rises flooded inland areas.¹¹³ Near-shore sediments were deposited with connate seawaters, and seawater intruded newly submerged aquifers made of non-marine sediment and bedrock.^{110,114,115} Subsequent isostatic rebound associated with deglaciation elevated these coastal

environments above sea level, trapping saline porewaters inland via permafrost aggradation due to cold paleoclimatic conditions. Marine transgressions reached up to 250 km inland around Hudson Bay, Canada and 1,000 km in western Siberia (Figure 1).^{116–118} In North America, approximately 650,000 km² of land may have been exposed to salt-water intrusion during the Holocene (Figure 1).

In both saline and continental permafrost settings, cryoconcentration can produce unfrozen brines exceeding 100 g L⁻¹ of total dissolved solids.^{110,111} Where confining hydrogeological conditions occur, these brines can be over-pressured by ice expansion, resulting in flowing artesian pressures that can expulse them to surface environments in the event of permafrost degradation.¹¹⁰ Thaw of permafrost can free these previously occluded brines and associated metals from confining conditions into the active layer and kill terrestrial plants.^{114,115,119–122} Release of high-salinity waters into fresh groundwater may also promote competitive desorption and transport of hazardous heavy metals. While direct case studies of these interactions are limited in a permafrost context, they have been observed in analogous non-permafrost environments such as coastal estuaries and aquifers experiencing salt-water intrusion.^{123–125} Issues related to water quality from thawing of saline permafrost remain poorly studied, although the higher melting point of saline permafrost makes it especially vulnerable to thaw, and its large spatial extent could make it a largescale feature of environmental concern.¹²⁶



Figure 6. Acid-rock drainage caused by sulfide-mineral oxidation in thawing permafrost regions. (A) Groundwater spring releasing acidity, sulfate, and metals from weathered black shale to Engineer Creek, Yukon (photo Elliott Skierszkan, Carleton University). The spring has a pH of 4.5, 4,800 mg L⁻¹ sulfate, 55 mg L⁻¹ Zn, and 12 mg L⁻¹ Ni. (B) Mixing of this spring with alkaline streamwater drives precipitation of metals as suspended particles transported in Engineer Creek (photo credit: Elliott Skierszkan, Carleton University). (C) Acid-rock drainage impacted streamwater mixing with the South McQuesten River in central Yukon (photo credit: Gary Hope, Gary; Na-Cho Nyak Dun First Nation). (D) Acid-rock drainage on a mountain slope of Macmillan Pass, Yukon (photo credit: John Dockrey, Lorax Environmental Services).

5. IMPLICATIONS, CHALLENGES, AND OPPORTUNITIES

Current research suggests substantial potential for metal release from thawing permafrost due to increased (bio)-geochemical, hydrological, and hydrogeological processes. Our understanding of these changes is conceptualized in Figure 5, and it is likely to evolve as further research unveils the full implications of thawing permafrost on metal mobility and water quality. Coupling between intensified groundwater circulation, mineral weathering, metal–organic matter interaction, redox reactions, and colloidal transport of metals leave substantial uncertainty around outcomes for water quality. Enhanced subsurface water interactions might generally be expected to increase metal fluxes but can also decrease them under certain conditions. For example, rising groundwater levels in topographic lows and groundwater discharge zones

might limit oxygen ingress into the subsurface, inhibit sulfide-mineral oxidation, and lead to precipitation of metals that form insoluble phases (e.g., secondary sulfides) under reducing conditions. Much research is needed to predict water quality shifts associated with thawing permafrost. Key research priorities include:

Priority 1: Expanding Long-Term Observatories in the Permafrost Zone. Tracking environmental change requires long-term (multidecadal) observations. A selection of research observatories exists in small headwater catchments,^{127–130} which can serve as sentinels of environmental change.¹⁴ However, more long-term observations are needed to better cover the range of climatic, geological, and geomorphological settings encompassed in the permafrost zone to better understand the effects of permafrost thaw on water quality at larger scales. Expanding observatories across different permafrost environments is crucial to inform watershed and land-use planning, industrial practices and regulation, and water-resource management. Reference sites unimpacted by local disturbance (e.g., mining, forestry, construction) are essential to disentangle water-quality changes driven directly by these disturbances against broader regional changes driven by permafrost thaw.^{26,131,132} Collaboration with local communities and industry stakeholders, which have unique insight to share from their regular presence on the land and vested interest in adaptive water management, can enhance the relevance and impact of these observatories.

Priority 2: Constrain Metal Mobilization Processes through Controlled Laboratory Experiments and Numerical Modeling. Controlled laboratory experiments can complement field observations by isolating the mechanisms of metal mobilization under thaw conditions at accelerated time scales. Research should investigate interactions among hydrogeological transport, temperature, microbial activity, organic matter cycling, mineral weathering, pH and redox shifts, cryoconcentration, freeze–thaw cycles, and colloidal transport. Advances in analytical chemistry will improve our understanding of metal–organic matter interactions and colloidal transport, which are especially important in organic-rich permafrost environments experiencing dynamic processes of freeze–thaw, metal–organic carbon interaction, and redox cycling.^{29,30,46,133} Continued advances in thermal-hydrological-chemical numerical models are essential to understand linkages between freeze and thaw, solute transport, and (bio)geochemical reactions governing metal transport.^{104,9,11,147}

Priority 3: Elucidate Relationships between Shifting Microbial Communities and Metal (Bio)geochemical Cycling. Microbial communities are active well below 0 °C.¹³⁴ Permafrost thaw alters microbial communities and metabolic activities,^{77,135–138} yet studies connecting these shifts to metal mobility remain limited.^{74,139,140} The permafrost microbiome is dominated by anaerobic heterotrophic metabolisms (e.g., fermentation, methanogenesis, sulfur and iron cycling) that strongly influence metal mobility by catalyzing redox reactions and altering porewater geochemistry.¹⁴⁰ Microbial respiration and detoxification pathways can also directly alter the mobility and bioavailability of various metals including arsenic,¹⁴¹ iron,¹⁴² mercury,¹⁴³ selenium,¹⁴⁴ and uranium.¹⁴⁵ Detailed multiomics approaches (metagenomics, metatranscriptomics, proteomics, metabolomics) alongside geochemical analyses will provide a clearer picture of how shifts in microbial activity related to permafrost thaw influence metal mobility.

Priority 4: Improve Permafrost Mapping, Forecasting, and Remote Sensing Applications to Water Quality. Anticipating metal response to thawing permafrost requires advances in permafrost mapping and forecasting.¹ While large-scale permafrost probability models are available,^{1,2,146} finer-scale (regional to local) models are essential to identify catchment-scale vulnerability to hydrological and (bio)geochemical changes from thawing permafrost, particularly in the discontinuous and sporadic permafrost zones where permafrost distribution is heterogeneous and permafrost is thawing fastest. Improved mapping of saline permafrost is also needed to mitigate environmental hazards associated with brines released during mining and construction activities.

Additionally, remote sensing tools are increasingly utilized to observe water-quality changes related to metal mobilization and permafrost thaw, and constitute an important area for rapid progress in remote permafrost regions where fieldwork logistics and complex and costly.^{22,88}

Priority 5: Introduce Adaptive Water Management Practices. Permafrost degradation has major implications for water management by altering the water chemistry, contaminant transport, and geotechnical stability. Industrial proponents, communities, and regulators must consider more flexible water-management approaches that account for shifts in water flowpaths and water chemistry. Relying on permafrost as a barrier against water movement and contaminant transport should be scrutinized, given projected permafrost degradation in the coming decades. Community and industrial water supply and management practices should also consider how these shifts might impact their water resources and plan accordingly.

6. SUMMARY

In this Perspective, we synthesized recent evidence that permafrost thaw drives substantial changes across the key variables governing metal mobility: water flowpaths; (bio)geochemical reactions involving liquid water interactions with minerals, microbes, and organic matter; and temperature-dependent kinetic and thermodynamic reactions. Our overall conclusion is that major shifts in (bio)geochemical cycles accompanying permafrost thaw introduce important shifts in metal mobility with uncertain outcomes for water quality. These changes define an emergent and previously underappreciated outcome of a warming cryosphere, and further research is needed to unravel ramifications for on water resources.

Understanding the environmental consequences of permafrost thaw on metal mobility requires collaborations across scientific and engineering disciplines and across sectors. Northerners, with their high reliance on local food and water supplies, have a particularly strong interest and role in understanding how climate change impacts their water resources. Insights from local observations, traditional knowledge, and community experience are invaluable for setting research priorities in a dynamic context of rapid environmental change.¹⁴⁸ Ultimately, challenges associated with thawing permafrost are best addressed through collaborative efforts combining the expertise of communities, industry, academia, government, and nonprofit groups to support water resource management under a changing climate.

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Notes

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