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# Anthropogenic contaminants in glacial environments II: Release and downstream consequences

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## Abstract

Anthropogenic contamination has been detected in glacial and proglacial environments around the globe. Through mechanisms of secondary release, these contaminants are finding their way into glacial hydrological systems and downstream environments, with potential to impact hundreds of millions of people who rely on glacial meltwater for water, food and energy security worldwide. The first part of our progress report outlined the sources and accumulation mechanisms of contaminants in glacial environments (Part I: Inputs and accumulation). Here we assess processes of contaminant release, pathways to downstream environments, and socio-environmental consequences. We reflect on the potential impacts these contaminants could have for human, ecosystem, and environmental health, as well as framing glacial contaminants within the context of the water-food-energy nexus. Improved understanding of these processes and impacts, while crucially embedding local knowledge, will help to develop key policy and mitigation strategies to address future risk of contaminant release from glaciers.

## Keywords

Cryosphere, anthropogenic, contaminants, glaciers, water security, food sovereignty, food security, environmental justice, pollution

## I Introduction

One billion people worldwide rely on glacial meltwater for uses such as crop irrigation and

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animal husbandry (Biemans et al., 2019), energy production (Carey et al., 2014; Mark et al., 2017), and domestic needs, including drinking water, food preparation and sanitation (Hodson, 2014). Populations in mountain glacier regions are at risk from contamination due to accumulation processes in glaciated environments and the substantial demand for glacier meltwater as a resource (Biemans et al., 2019; Rowan et al., 2018; Synnove et al., 2018). It is thus important to examine the range of processes and mechanisms controlling contaminant levels in glaciated environments, and assess how this can impact on water, food, and energy security, as well as on human and ecosystem health.

Our previous progress report, *Part I: Inputs and accumulation* (Beard et al., 2022), reviewed current knowledge of six main contaminants found within glacial environments (black carbon, fallout radionuclides, potentially toxic elements, microplastics, nitrogen-based contaminants, persistent organic pollutants), with a focus on their sources, and processes of transport and accumulation. Here we review the factors controlling the release of these contaminants from glaciers and the potential impacts this can have downstream. The aim of this progress report is thus to look at contaminants through an eco-social lens to understand how future glacier melt could pose risks to both nature and society. We identify gaps in knowledge where further work is required to contribute to the development of appropriate policy, mitigation, and adaptation strategies in order to protect glacial meltwater as an essential resource, and to sustain ecosystem and human health in glaciated environments.

## II Factors controlling secondary contaminant release

Contaminants stored within glaciers are primarily transported into downstream environments through downwasting (i.e. the thinning of a glacier due to the melting of ice), glacier retreat (Sommer et al., 2020), and through fluxes of meltwater and sediments (Zhu et al., 2020). The timing of the release of meltwater and the contained contaminants from glaciers depends on various factors, including water chemistry

(Staniszewska et al., 2020), glacier hydrology (Milner et al., 2017), climate and local weather (Hung et al., 2022), glacier dynamics (Barry, 2006), and duration of the melt period (Bizzotto et al., 2009). This section discusses some of these factors and their contribution to the release of glacial contaminants.

### 2.1 Climate and weather

It is widely recognised that glaciers are shrinking and retreating globally in response to the planet's warming climate (e.g. Braithwaite and Hughes, 2022). However, area-specific weather phenomena such as El Niño Southern Oscillation (ENSO) events have also been shown to increase both rainfall and glacier recession within areas such as the Andes and the Antarctic ice shelf (López-Moreno et al., 2014; Mernild et al., 2015; Seehaus et al., 2019; Steig et al., 2012; Veetil et al., 2017; Veetil and Simões, 2019). Extended and seasonal drought periods, coupled with warm temperatures, are known to increase melting events within glaciated catchments (Van Tiel et al., 2021). Similarly, studies have shown that monsoonal weather events have comparable impacts on Himalayan glaciers, due to the scrubbing effect of precipitation on airborne contaminants (Pant et al., 2020). The atmospheric scavenging of contaminants varies during storm events, due to higher velocity winds and heavy precipitation within short timespans (Offenberg and Baker, 2002). Model predictions have shown that both ENSO events and monsoon seasons are becoming more intense, and the number of localised storm events will increase with a warming climate (Konisky et al., 2016; Rummukainen, 2012; Stott, 2016).

Climate models predict that within 25–50 years, precipitation could increase by up to 20–30% in the Arctic (IPCC, 2018) and 26–31% in the Himalayas (Ali and Khan, 2021). These expected changes to global precipitation will have significant implications for the dynamics of contaminant transport and increased washing of contaminants from glacier surfaces by rainfall and/or higher ratios of contaminant release from meltwaters with decreased melt (Hock et al., 2005). Glaciated regions such as the Andes are more vulnerable to extreme weather events due to the

strong orographic variability of mountain ranges (Poveda et al., 2020). Some areas of the tropical belt of South America are predicted to become drier and more arid as the climate changes. A drier climate means additional dust, a higher likelihood of wildfires, and increased drought periods (Pritchard, 2017). It is important to understand the implications that weather patterns and climatic changes will have on contaminant release within the cryosphere in order to better predict the impact of contaminant release on downstream water resources.

## 2.2 Glacier recession

Glacier recession has multiple implications for wider glacial systems, including changes to meltwater and discharge, the quality and quantity of water resources, direct and indirect socio-economic impacts from water scarcity, and changes to downstream ecosystems and geomorphology. Additionally, there may potentially be an increase in the concentration of contaminants within water systems, via a reduction in contaminant dilution due to reduced water quantity (Guittard et al., 2020). Research has shown that rapid glacier recession can release stored contaminants and sediments downstream in high concentrations (Bogdal et al., 2009; Kang et al., 2009). Glaciers are efficient erosion agents (Koppes and Montgomery, 2009) and are a dominant sediment source in many mountain catchments (Tsyplenkov et al., 2020; Yao et al., 2020) and polar landscapes (Dubnick et al., 2017; Overeem et al., 2017; Witus et al., 2014). Changes in sediment discharge from glaciers affects water quality, which can have significant impacts for downstream communities and ecosystems (Stott and Convey, 2020).

Furthermore, the sediment itself can also be seen as a contaminant for many communities and industries (CCME, 2002; Chapman et al., 2013), as it can require management, monitoring and removal. Ice surface materials, such as cryoconite (Beard et al., 2022), can be easily mobilised by supraglacial meltwater, resulting in the potential for contaminants sorbed onto particles to enter the downstream hydrological system. Some ice surfaces (e.g. flat ice caps) store much larger quantities of sediment (Figure 1) than steeper valley glaciers.



**Figure 1.** An example of mass sediment (cryoconite) storage on the surface of the Flade Isblink ice cap, Greenland. Photography by Dylan B. Beard. For interpretation of the references to colours in this figure legend, refer to the online version of this article.

As a result of climate warming, glacier recession may lead to increased risk from contaminants and associated hazards. Given that water security relies on both water quantity and quality, mitigating the impacts on the quality of glacier-fed waters is crucial. There are only a handful of detailed studies available at present to underpin our understanding of current and future regulating services of glacier-fed rivers (e.g. Dorava and Milner, 2000; Maldonado et al., 2011; Milner et al., 2017)

## 2.3 Localised hazards and event-scale contaminant release

Mountain ranges are prone to mass movements of snow, ice, rock and sediment due to characteristics such as steep slopes, high topographic relief, seismic

activity, and hazard cascades (Shugar et al., 2021). These mass movements, such as avalanches and rockfall, can occur in response to natural instabilities in the snowpack or mountain permafrost (Owen, 1991), or in response to anthropogenic activity and accidents (Clason et al., 2015). The rapid mass movement of material on glacier surfaces can scrub contaminants from the supraglacial environment, transporting them downslope with other materials such as snow, ice blocks and water, leading to accumulation of contaminants at lower elevations (Lawson, 1982; Owen, 1991). Once in the ablation zone, contaminants are more susceptible to rapid melting and release into downstream environments (Hodson, 2014).

Once released into meltwater, glacial lakes can accumulate contaminants in lake-bottom sediments (Beard et al., 2022), but during glacier lake outburst floods (GLOFs) these sediments can be mixed into the water and released downstream in a concentrated burst (Bazai et al., 2021; Harrison et al., 2018; Vandekerkhove et al., 2021), also acting to increase the area over which sediments and contaminants are spread within downstream environments. GLOFs are predicted to become more frequent due to increased glacier retreat and high-energy weather events caused by a warming climate (Veh et al., 2022; Zheng et al., 2021). These localised hazards have the potential to increase the secondary release of glacial contaminants and therefore need to be considered when evaluating future environmental risks.

### III Threats to humans, flora, and fauna

It is crucial to evaluate the risks associated with the accumulation, release and deposition of contaminants into downstream environments, to establish effective policies and mitigation strategies for managing the risks of glacial contaminants to the wider environment. To date, there has been very limited research into the implications of contaminant release from glaciers. Nonetheless, this next section outlines current understanding, particularly in relation to contaminants in other environmental systems, and how this knowledge can be applied to the assessment of glaciated environments.

#### 3.1 Contaminant toxicity and implications for flora, fauna, and human health

Ecosystems in glaciated environments depend on a delicate balance of nutrient availability and environmental chemistry for survival and optimal living conditions. Therefore, the re-introduction of anthropogenic contaminants into meltwater could have detrimental implications for both human and ecosystem health (Borgå et al., 2022). After being released into glaciated environments, contaminants are often diluted into safe concentrations once they enter water systems, due to the increased ratio of water to contaminants (Baccolo et al., 2020) and mixing with inorganic sediments (McGovern et al., 2022). However, these concentrations can rise to unsafe levels via two processes: (i) bioaccumulation, which is the gradual accumulation of a substance within an organism caused when the organism absorbs the substance at a faster rate than the loss or elimination (Vorkamp and Rigét, 2014); and (ii) biomagnification, which is the progressive build-up of toxic substances by successive trophic levels (Clayden et al., 2015; Van Der Velden et al., 2013). Both processes can pose threats to the health of apex predators, as well as to humans that ingest organisms at high trophic levels. There are significant known impacts from the ingestion of contaminated flora and fauna, particularly those with biomagnified contaminants (Kumar et al., 2019). The uptake from contaminated and eco-toxic glacier-fed water sources could thus pose issues for both wildlife and human health (Carbery et al., 2018; Donaldson et al., 2010, 2016; Hembrom et al., 2020; Kallenborn et al., 2011).

The release of toxic contaminants into hydrological systems in glacial regions also presents an immediate exposure risk to aquatic biological communities (Bizzotto et al., 2009). The ecosystems within these environments often have low biodiversity due to reduced nutrient availability and harsh environmental conditions, which results in lower species stability and greater food chain vulnerability (Bizzotto et al., 2009). Similarly, increased levels of contaminants have been implicated in the disruption of animal physiology (Edwards et al., 2006; Saaristo et al., 2018). Furthermore, lowered pH and the



introduction of dissolved metals and potentially toxic elements into habitats is stressful for most organisms, with sensitive taxa and life stages negatively affected where pH is <5.5 (Jennings et al., 2000). While mobile organisms, such as fish, can move away from stressful environments and contaminant hotspots, stationary organisms found in glaciated areas, such as algae, mosses, and lichens, cannot escape and must either adapt, or not survive. Whilst the health risks posed by the release of contaminants from glaciers remains poorly understood, the impacts of contaminants that have been evaluated in other environments can be used to estimate potential risks within glaciated environments (Table 1).

Many contaminants also cause human health impacts due to toxicity and carcinogenic properties (Erickson et al., 2019; Miner et al., 2018). These impacts, which affect both physical and mental health, can be more severe for rural and Indigenous communities due to a lack of accessibility to appropriate services, social vulnerability, and reduced medical intervention and monitoring (Mead et al., 2013; Wilson et al., 2018). To date there has been limited research conducted into the potential harm caused to people consuming local crops and animal produce in glaciated regions.

### 3.2 Impacts of contaminants on microbial communities

Microbial communities not only influence the mobility and toxicity of contaminants (Beard et al., 2022), but can also be affected by them. Microbial communities in other areas, such as salt marshes, have demonstrated that exposing bacteria to a variety of microplastics (e.g. polyethylene, polyvinyl chloride, polyurethane foam, or polylactic acid) affects the composition of microorganisms and biogeochemical processes such as nitrogen cycling (Prata et al., 2019). Microplastics have also been found to be a favourable substrate for microorganisms in these areas (Hale et al., 2020; Seeley et al., 2020). Other contaminants, such as fallout radionuclides (FRNs) and potentially toxic elements (PTEs), can also affect the microbial community structure and functionality (Alrumman et al., 2015; Sutton et al., 2013). FRN contamination can reduce microbial biomass in soils

and sediments (Khovrychev et al., 1994; White and Gadd, 1990). This in turn can negatively impact nutrient cycling and availability, plus soil health and recovery (Smith and Paul, 1990). Increased deposition of nitrogen-based contaminants on glaciers since pre-industrial time has likely led to a reduced demand for microbial nitrogen fixation on glaciers, as nitrogen is no longer a limiting factor throughout most of the melt season (Telling et al., 2011, 2012).

## IV Glacial contaminants, the water-food-energy nexus and environmental justice

The water-food-energy (WFE) nexus is established in sustainability studies, interlinking water, food, and energy security in the context of growing demands due to population growth, climate change, and shifting environments (Cai et al., 2018; D'Odorico et al., 2018; Scanlon et al., 2017). The nexus approach illustrates the intersectionality between the primary resources that are required for a secure future and calls for a cross-sector approach to meet global demands. As such, the World Economic Forum sees it as a priority development goal, with the framework having high importance within international policy (Terrapon-Pfaff et al., 2018). However, the WFE nexus has been criticised for being apolitical and ignoring the importance of environmental justice (Allouche et al., 2019).

Studies have discussed the interlinkages between water, energy, and food within glaciated catchments (Faramarzi et al., 2019; Momblanch et al., 2019; Wang et al., 2021b), however, there is a paucity of data exploring the role which glacial contaminants may play in the nexus. Meltwater is at the heart of the WFE nexus in many glacial regions, and crucial for downstream water resources, food production, and for energy generation (Momblanch et al., 2019; Rasul, 2014). Figure 2 shows the primary threats that glacial contaminants pose to the WFE nexus.

### 4.1 Water scarcity

It has been estimated that 1.8 billion people will be living with absolute water scarcity by 2025, and two

**Table 1.** Example toxicologic implications of contaminants for: Fl (flora); Fa (fauna); Hu (humans), and studies in which these examples can be found in other environmental systems.

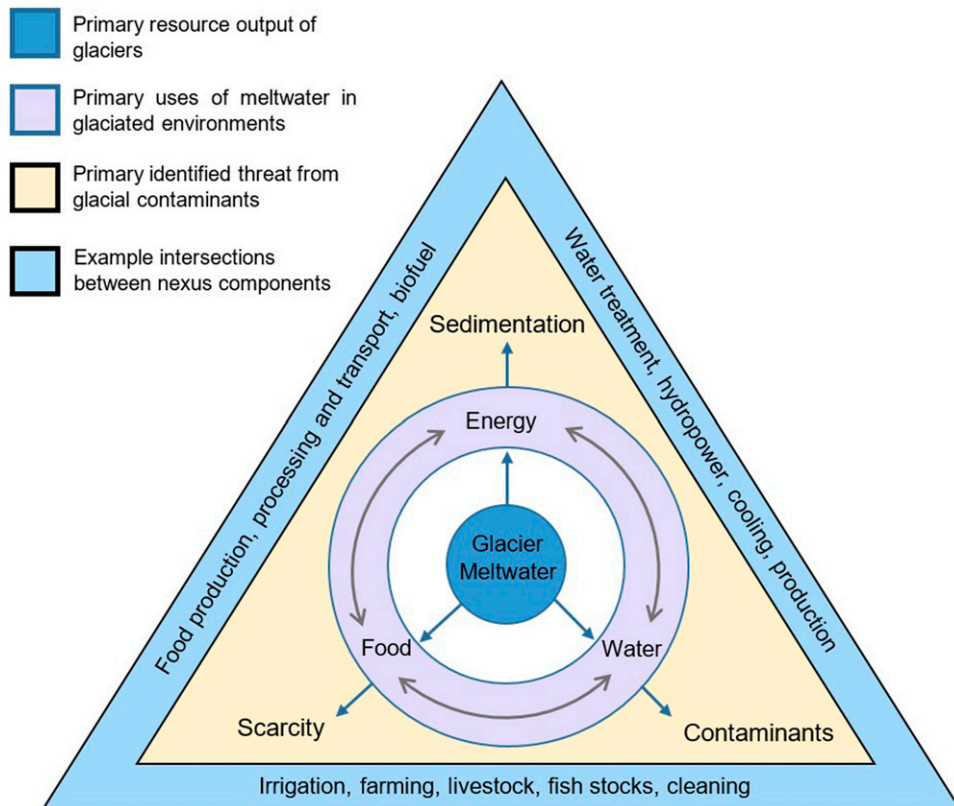
Risk to	Toxicologic impacts caused by contaminant(s)	Contaminant class					
		BC	FRNs	PTEs	MPs	NBCs	POPs
Fl Fa Hu	Photosynthesis/oxygen intake	Knauer et al., 2007	Shaw and Bell, 1994	Manara, 2012	Colzi et al., 2022	Camargo and Alonso, 2006	Tomar et al., 2019
	Biodiversity	Zainab et al., 2022	Wilhelmsson et al., 2013	Tovar-Sánchez et al., 2018	Guzzetti et al., 2018	Nie et al., 2009	Jones, 2021
	Nutrient uptake	Foereid et al., 2011	Shaw and Bell, 1994	Manara, 2012	Wright et al., 2013	Camargo and Alonso, 2006	Adeola, 2004
	Growth/yield	Brown, 2014	Shaw and Bell, 1994	Manara, 2012	Guzzetti et al., 2018	Chen et al., 2019a	Chen et al., 2019b
	Fertility/reproduction	Foereid et al., 2011	Suchanek, 1994	Canipari et al., 2020	Wright et al., 2013	Camargo and Alonso, 2006	Alharbi et al., 2018
	Cellular implications	Wang et al., 2021	Rajković et al., 2006	Engwa et al., 2019	Hale et al., 2020	Chen et al., 2019a	Chen et al., 2019b
	Cardiovascular/endocrine	Kirrane et al., 2019	Rajković et al., 2006	Engwa et al., 2019	Wright et al., 2013	Camargo and Alonso, 2006	Hoondert et al., 2021
	Neurological/brain function	Sunyer, 2008	Gagnaire et al., 2011	Engwa et al., 2019	Yong et al., 2021	Camargo and Alonso, 2006	Wahlang, 2018
	Carcinogenic	Lin et al., 2019	Suchanek, 1994	Engwa et al., 2019	Wright et al., 2013	Nie et al., 2009	Wahlang, 2018

Contaminant classes include: black carbon (BC); fallout radionuclides (FRNs); potentially toxic elements (PTEs); microplastics (MP); nitrogen based contaminants (NBCs); persistent organic pollutants (POPs). Grey shading indicates potential risk(s) to either Fl, Fa, or Hu.

thirds of the global population could be subject to water stress (FAO, 2020), defined as the threshold for meeting the water requirements for agriculture, industry and domestic purposes (Kaltenborn et al., 2010). Water is a crucial resource for human health, resource production, and economic development,

and as such, access to clean water is an important sustainable development goal (UN SDG 6), and a fundamental human right (Hering et al., 2016).

Glaciers are often referred to as “water towers”, storing vast amounts of the Earth’s freshwater (Viviroli et al., 2011), which is a crucial element in



**Figure 2.** The water-food-energy nexus in the context of meltwater use and primary threats from glacial contaminants. For interpretation of the references to colours in this figure legend, refer to the online version of this article.

sustaining both human and ecosystem health (WHO, 2008). Contaminants released from glaciated environments are most mobile in fluvial settings, due to the speed at which sediment is transported in water and the gravity driven movements downstream (Choudhary et al., 2020; Strumness et al., 2004). High levels of nitrates can lead to eutrophication which can reduce water quality and endanger the sustainability of riverine ecosystems (Erickson et al., 2019; Owens et al., 2019; Schriks et al., 2010). Additionally, natural processes like weathering, and anthropogenic activities like mining, can result in high acidity of glacier-fed water. Leachate and water run-off can then re-enter water systems with an increased concentration of contaminants (Chen et al., 2020; Pratt and Fonstad, 2017). For

example, in parts of the Andes, where geology is iron rich, glacier retreat and metal mining has resulted in very low pH glacial tributaries with high levels of acid rock drainage, making water un-useable for the local populations (Fortner et al., 2011; Meza et al., 2015; Synnove et al., 2018).

Reductions in either water quality or quantity can have life-threatening implications to communities who rely on these resources (Vergara et al., 2011), especially where there is a lack of both water treatment and water testing regulations in many of the rural environments where many Indigenous Peoples reside (Bressler and Hennessy, 2018; Daniel et al., 2021). Contamination of water in glacial catchments is therefore a huge challenge for, and risk to, local water security and health.



## 4.2 Food security

Food security means that all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their food preferences and dietary needs for an active and healthy life (FAO, 2020). The main emphasis of food security is in relation to inequitable food availability worldwide (Prosekov and Ivanova, 2018), with considerably less focus on the safety of food resources within the context of contaminants. Many populations living in, or near, glaciated regions use glacier meltwater for farming, irrigation, and animal husbandry (Meza et al., 2015). The use of land within close proximity to glaciers may increase the likelihood that contaminants will leach into the soil and be consumed by crops and grazing animals, affecting the quality of produce as well as posing risks to human health (Carey, 2013; Guittard et al., 2017; Hansen et al., 2021; Synnove et al., 2018). Furthermore, the accumulation of contaminants can reduce the fertility of the soil, prevent the uptake of nutrients, and increase the uptake of toxic elements by plants, reducing the sustainability of crops and threatening the survival of ecosystems and food security (Bargagli, 2008; Howells et al., 2018).

Organic farming results in higher concentrations of contaminants than intensive farming due to associated practices such as the use of waste-based manures and organic amendments (Diacono and Montemurro, 2011; Ramakrishnan et al., 2021). It has been reported that Indigenous and rural communities use more natural farming practices (Chaudhry and Chaudhry, 2011; Dey and Sarkar, 2011). Thus, it is possible that these crops may be susceptible to high contaminant concentrations and cascading environmental hazards from the introduction of more contaminants from the glacial system. Conversely, intensive farming practices lead to higher soil loss, increased fertilizer use, and the introduction of synthetic pesticides and fungicides (Solgi et al., 2018), which can be equally, if not more problematic. It is therefore important to consider localised land use and practices when looking to assess contaminant risk from glaciers.

Communities that rely on livestock and herding in polar and alpine regions are more susceptible to the

risks associated with contaminants in glaciated environments, due to the grazing habits of herds and the biomagnification of contaminants within larger mammals, notably reindeer and caribou (Hong et al., 2011; Guillen et al., 2012; Stocki et al., 2016). For example, Sámi people, a community that live in northern areas of Scandinavia and Russia (Sápmi), have a culture based primarily around reindeer herding and the spiritual connection between people and their animals (Ness and Munkejord, 2021; Österlin, 2020). Reindeer largely feed on lichens, mosses, and fungi – all organisms that have been found to readily absorb and retain contaminants. Their style of herding involves an annual migration, sometimes over 1000 km, mostly across glaciated or peri-glaciated landscapes (Forbes, 2013; Golovnev and Osherenko, 2018). The increased exposure to the vast ground they cover means that they are far more likely to encounter contaminated zones within glaciated environments.

Risks to reindeer were identified and assessed after the Chernobyl disaster in 1986 (Skuterud et al., 2005; Skuterud and Thørring, 2012). This resulted in reindeer health monitoring, which led to a reduction of ingested doses of FRN contamination within Sámi communities (Kurtio et al., 2010; Skuterud and Thørring, 2012). However, many other contaminants have not undergone such investigation and evaluation; this example shows the considerable need for assessment and mitigation implementations to help reduce exposure to other contaminants identified in glacial regions. Additionally, the bio-accumulation of multiple contaminants in the same area could raise the environmental risk of an area to above a level of concern and jeopardise the livelihoods of these communities (Mora et al., 2022). Therefore, it is important to investigate the interactions between contaminants when in the same environment and how these contaminants can impact crop health, food quality, and sustainability of resources.

## 4.3 Energy resources

Energy generation fits into the WFE nexus in many ways, such as water used for cooling in energy production, and energy used for food production.

However, in the context of glacial contaminants, the primary threats are to hydropower systems, which are often located in glacial regions. Sediment itself can be considered as a contaminant, by affecting sediment flux, water turbidity, and congestion in hydropower dams (Pralong et al., 2015), resulting in additional costs for the removal of sediment over time. The finer grained sediments carry contaminants picked up from the water, as well as trapping nutrients essential to aquatic ecosystems. These contaminant-rich sediments are then released in bulk via sediment removal strategies such as sluicing, dredging, or flushing (Davidson et al., 2005). These can be hazardous to the environment if not done with consideration to contaminant loads. As demand and pressure on global water resources increases, it is likely that treated water will be prioritised for municipal and agricultural usage, due to the need for better water quality in these sectors. Therefore, water with a lower quality will likely be distributed for energy production, particularly in areas with negative water budgets.

#### 4.4 Environmental injustice

The Environmental Protection Agency defines environmental justice as “the fair treatment and meaningful involvement of all people regardless of race, colour, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies” (EPA, 2020: p. 47). Socio-politically, glaciers are currently an important marker for climate change impacts, and have been discussed at international events such as the G7 and G20 summits. Both the preservation and conservation of glacier environments, as well as the ecological and social impacts of glacier retreat, have been the subject of global media coverage and a significant political focus (Brugger et al., 2013; Carey et al., 2016, 2021; Marr et al., 2022; Taillant, 2015; Walker-Crawford, 2021). However, the spotlight on these factors has not yet translated to an increase in research funding needed to improve our understanding of the manifold impacts of glacier change, nor marked changes to climate policy. In addition, there is insufficient research into the

impact and effects of contaminants to Indigenous Peoples within glaciated catchments, which has prevented community governance (Nuttall, 2018, 2021; Wilson et al., 2018), resulting in inadequate access to water testing and treatment; lack of information about contaminant risk in their current environment; and a lack of socio-political voice that would enable Indigenous and local communities the opportunity to be able to have a say or alter their situation (Huntington et al., 2019; Ryder et al., 2021; Tsosie, 2007).

Within glaciated regions, there is still a lack of community input and collaboration to the design, development, and implementation of policy and mitigation strategies, particularly those affecting Indigenous Peoples (McGregor et al., 2020). Communities who live in close proximity to glacial areas often have a lack of political voice, limited access to resources, and are unable to change their exposure to contaminants within proglacial environments, without support from external services and implementation of interventions (Hegglin and Huggel, 2008). These are key socio-political indicators of vulnerability across the globe and suggest that addressing social injustices is crucial to fully understanding the impacts that glacial contaminants may have on human, ecosystem, and environmental health.

Whilst the physical impacts of glacier behaviour, such as regulating climate, contributing to landscape evolution, and providing water resources is now very well understood, the socio-cultural impacts such as the stimulation of art and literature, tourist economies, community livelihoods, globalisation, and political agendas have largely been omitted in the context of glacial contaminants and the potential negative implications to these aspects (Hovelsrud et al., 2011). Similarly, there has been considerably less research on the negative health impacts from contaminants to the communities living within, and immediately downstream from, glaciated environments, nor on the impacts on the social, cultural, religious, and spiritual importance of glaciers.

In addition to better incorporating key justice issues within research, we must also recognise that

traditional ecological knowledge (TEK) can be a vital ingredient for improving understanding of environmental quality (Allison, 2015; Nelson and Shilling, 2018). A substantial challenge of mitigating future glaciological contamination is the notion that the regions and communities impacted by glacial contaminants are not the primary producers/emitters of those contaminants. It is therefore important to use TEK, co-design policies, and enable collaborative management with the communities who live in areas impacted by glacial contaminants. To the best of our knowledge, no previous studies have integrated TEK to design data collection, assess future risk, or develop mitigation strategies, within the context of glacial contaminants. In addition, raising awareness of contaminant transport pathways to polluting nations and industries can support the mitigation of risks from contaminants globally.

## V Summary

Anthropogenic contamination has been detected in glacial and proglacial environments around the globe, and research has begun to assess and quantify the level and spatial distribution of contaminants within the cryosphere (Beard et al., 2022). More research is required to address gaps in knowledge on areas of potential risk from the release of glacially stored contaminants, and the impacts of these contaminants for human and ecosystem health, and livelihoods. We highlight the need to incorporate Traditional Ecological Knowledge (TEK) in research to better share and disseminate information about glacial contaminants, in addition to contributing to the development of strategies to protect future water resources as glaciers continue to melt. Furthermore, the water-food-energy nexus framework can be an important tool in the progression of future research concerning both meltwater quality and quantity. It is essential to ensure that communities who are at risk from glacial contaminants are at the forefront of the development of key policy and mitigation strategies, and can regain agency and self-determination. From this, we can build a better foundation for understanding and quantifying the current and future risks to humans and ecosystems

posed by anthropogenic contaminants in glacial environments.

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