Progress Report

Anthropogenic contaminants in glacial environments II: Release and downstream consequences

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Dylan B Beard and Caroline C Clason
School of Geography, Earth and Environmental Sciences, University of Plymouth, Plymouth, UK

Sally Rangecroft
School of Geography, Earth and Environmental Sciences, University of Plymouth, Plymouth, UK

School of Geography, College of Life and Environmental Sciences, University of Exeter, Exeter, UK

Ewa Poniecka
Department of Environmental Microbiology and Biotechnology, University of Warsaw, Warsaw, Poland

Kim J Ward and Will H Blake
School of Geography, Earth and Environmental Sciences, University of Plymouth, Plymouth, UK

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

Corresponding author:
Dylan B Beard, School of Geography, Earth and Environmental Sciences, University of Plymouth, SoGEES, B409 Portland Square, Plymouth PL4 8AA, UK.
Email: dylan.b.beard@gmail.com

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; Veettil et al., 2017; Veettil 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 is 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					
Fl	Fa	Hu		BC	FRNs	PTEs	MPs	NBCs	POPs
■	■		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

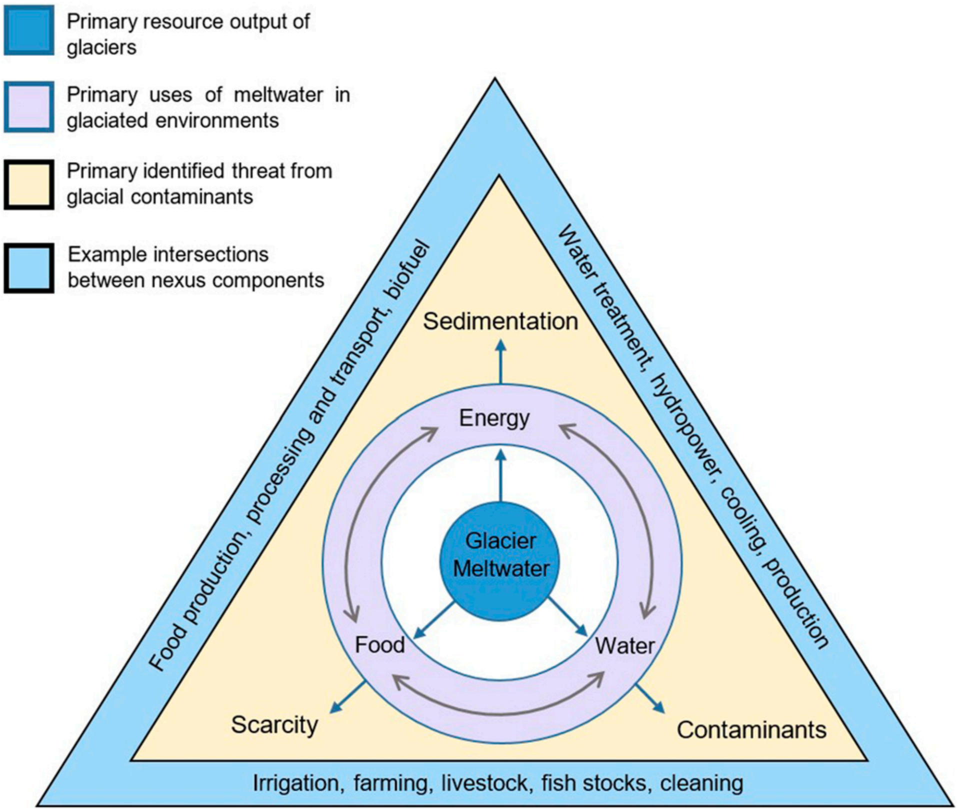

Figure 2. The water-food-energy nexus in the context of meltwater use and primary threats from glacial contaminants. For interpretation of the references to colours in this figure legend, refer to the online version of this article.

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 (Kurttio 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 bioaccumulation 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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ORCID iDs

Dylan B Beard https://orcid.org/0000-0001-7289-8225
Ewa Poniecka https://orcid.org/0000-0002-0772-8630

References

Adeola FO (2004) Boon or bane? The environmental and health impacts of persistent organic pollutants (POPs). *Human Ecology Review* 11(1): 27–35.

Alharbi OML, Basheer AA, Khattab RA, et al. (2018) Health and environmental effects of persistent organic pollutants. *Journal of Molecular Liquids* 263: 442–453. DOI: 10.1016/j.molliq.2018.05.029

Ali SR and Khan JN (2021) Climate predictions for central Kashmir of great Himalayas under different emission scenarios of IPCC. *MAUSAM* 72(22): 323–330.

Allison EA (2015) The spiritual significance of glaciers in an age of climate change. *WIREs Climate Change* 6(5): 493–508. DOI: 10.1002/wcc.354

Allouche J, Middleton C and Gyawali D (2019) *The Water–Food–Energy Nexus: Power, Politics, and Justice*. Oxon and New York: Routledge.

Alrumman SA, Standing DB and Paton GI (2015) Effects of hydrocarbon contamination on soil microbial community and enzyme activity. *Journal of King Saud University - Science* 27(1): 31–41. DOI: 10.1016/j.jksus.2014.10.001

Baccolo G, Łokas E, Gaca P, et al. (2020) Cryoconite: an efficient accumulator of radioactive fallout in glacial environments. *The Cryosphere* 14(2): 657–672. DOI: 10.5194/tc-14-657-2020

Bargagli R (2008) Environmental contamination in Antarctic ecosystems. *Science of The Total Environment* 400(1): 212–226. DOI: 10.1016/j.scitotenv.2008.06.062

Barry RG (2006) The status of research on glaciers and global glacier recession: a review. *Progress in Physical Geography: Earth and Environment* 30(3): 285–306. DOI: 10.1191/0309133306pp478ra

Bazai NA, Cui P, Carling PA, et al. (2021) Increasing glacial lake outburst flood hazard in response to surge glaciers in the Karakoram. *Earth-Science Reviews* 212: 103432. DOI: 10.1016/j.earscirev.2020.103432

Beard DB, Clason CC, Rangecroft S, et al. (2022) Anthropogenic contaminants in glacial environments I: Inputs and accumulation. *Progress in Physical Geography* 46: 03091333221107376. DOI: 10.1177/03091333221107376

Biemans H, Siderius C, Lutz AF, et al. (2019) Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic plain. *Nature Sustainability* 2: 594–601. DOI: 10.1038/s41893-019-0305-3

Bizzotto EC, Villa S, Vaj C, et al. (2009) Comparison of glacial and non-glacial-fed streams to evaluate the loading of persistent organic pollutants through seasonal snow/ice melt. *Chemosphere* 74(7): 924–930. DOI: 10.1016/j.chemosphere.2008.10.013

Bogdal C, Schmid P, Zennegg M, et al. (2009) Blast from the past: melting glaciers as a relevant source for persistent organic pollutants. *Environmental Science & Technology* 43(21): 8173–8177. DOI: 10.1021/es901628x

Borgå K, McKinney MA and Routti H (2022) The influence of global climate change on accumulation and toxicity of persistent organic pollutants and chemicals of emerging concern in Arctic food webs. *Environmental Science: Processes & Impacts*. DOI: 10.1039/D1EM00469G

Braithwaite RJ and Hughes PD (2022) Positive degree-day sums in the Alps: a direct link between glacier melt and international climate policy. *Journal of Glaciology* 68(271): 1–11. DOI: 10.1017/jog.2021.140

Bressler JM and Hennessy TW (2018) Results of an arctic council survey on water and sanitation services in the Arctic. *International Journal of Circumpolar Health* 77(1): 1421368. DOI: 10.1080/22423982.2017.1421368

Brown A (2014) Crop-yield drivers. *Nature Climate Change*, 4(12): 1050. DOI: 10.1038/nclimate2458

Brugger J, Dunbar KW, Jurt C, et al. (2013) Climates of anxiety: comparing experience of glacier retreat across three mountain regions. *Emotion, Space and Society* 6: 4–13. DOI: 10.1016/j.emospa.2012.05.001

Cai X, Wallington K, Shafiee-Jood M, et al. (2018) Understanding and managing the food-energy-water nexus – opportunities for water resources research. *Advances in Water Resources* 111: 259–273. DOI: 10.1016/j.advwatres.2017.11.014

Camargo JA and Alonso Á (2006) Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: a global assessment. *Environment International* 32(6): 831–849. DOI: 10.1016/j.envint.2006.05.002

Canipari R, De Santis L and Cecconi S (2020) Female fertility and environmental pollution. *International Journal of Environmental Research and Public Health* 17(23): 8802. DOI: 10.3390/ijerph17238802

Carbery M, O'Connor W and Palanisami T (2018) Trophic transfer of microplastics and mixed contaminants in the marine food web and implications for human health. *Environment International* 115: 400–409. DOI: 10.1016/j.envint.2018.03.007

Carey M (2013) Glacier runoff and human vulnerability to climate change: the case of export agriculture in Peru (Invited). *AGU Fall Meeting Abstracts* 21: GC21E–02.

Carey M, Baraer M, Mark BG, et al. (2014) Toward hydro-social modeling: merging human variables and the social sciences with climate-glacier runoff models (Santa River, Peru). *Journal of Hydrology* 518: 60–70. DOI: 10.1016/j.jhydrol.2013.11.006

Carey M, Jackson M, Antonello A, et al. (2016) Glaciers, gender, and science: a feminist glaciology framework for global environmental change research. *Progress in Human Geography* 40(6): 770–793. DOI: 10.1177/0309132515623368

Carey M, McDowell G, Huggel C, et al. (2021) A socio-cryospheric systems approach to glacier hazards, glacier runoff variability, and climate change. In: Haeberli W and Whiteman C (eds) *Snow and Ice-Related Hazards, Risks, and Disasters*. Second Edition. Amsterdam, Oxford and Cambridge: Elsevier, pp. 215–257. DOI: 10.1016/B978-0-12-817129-5.00018-4

CCME (2002) Canadian Water Quality Guidelines for the Protection of Aquatic Life - Total Particulate Matter. In: *Canadian environmental quality guidelines, 1999*. Winnipeg: Canadian Council of Ministers of the Environment, p. 13.

Chapman PM, Wang F and Caeiro SS (2013) Assessing and managing sediment contamination in transitional waters. *Environment International* 55: 71–91. DOI: 10.1016/j.envint.2013.02.009

Chaudhry DA and Chaudhry H (2011) Indigenous farming practices and sustainable rural development: a case of indigenous agricultural practices in a Punjabi village of Sheikhupura District. *FWU Journal of Social Sciences* 5: 98–128.

Chen H, Wang C, Li H, et al. (2019a) A review of toxicity induced by persistent organic pollutants (POPs) and endocrine-disrupting chemicals (EDCs) in the nematode Caenorhabditis elegans. *Journal of Environmental Management* 237: 519–525. DOI: 10.1016/j.jenvman.2019.02.102

Chen M, Zeng C, Zhang F, et al. (2020) Characteristics of dissolved organic matter from a transboundary himalayan watershed: relationships with land use, elevation, and hydrology. *ACS Earth and Space Chemistry* 4(3): 449–456. DOI: 10.1021/acsearthspacechem.9b00329

Chen Q, Wang M, Zhang J, et al. (2019b) Physiological effects of nitrate, ammonium, and urea on the growth and microcystins contamination of Microcystis aeruginosa: implication for nitrogen mitigation. *Water Research* 163: 114890. DOI: 10.1016/j.watres.2019.114890

Choudhary S, Nayak GN and Khare N (2020) Source, mobility, and bioavailability of metals in fjord sediments of Krossfjord-Kongsfjord system, Arctic, Svalbard. *Environmental Science and Pollution Research* 27(13): 15130–15148. DOI: 10.1007/s11356-020-07879-1

Clason CC, Coch C, Jarsjö J, et al. (2015) Dye tracing to determine flow properties of hydrocarbon-polluted Rabots glaciär, Kebnekaise, Sweden. *Hydrology and Earth System Sciences* 19(6): 2701–2715. DOI: 10.5194/hess-19-2701-2015

Clayden MG, Arsenault LM, Kidd KA, et al. (2015) Mercury bioaccumulation and biomagnification in a small Arctic polynya ecosystem. *Science of the Total Environment* 509: 206–215. DOI: 10.1016/j.scitotenv.2014.07.087

Colzi I, Renna L, Bianchi E, et al. (2022) Impact of microplastics on growth, photosynthesis and essential elements in Cucurbita pepo L. *Journal of Hazardous Materials* 423: 127238. DOI: 10.1016/j.jhazmat.2021.127238

Daniel D, Pande S and Rietveld L (2021) Socio-Economic and psychological determinants for household water treatment practices in Indigenous–Rural Indonesia. *Frontiers in Water* 3: 25. DOI: 10.3389/frwa.2021.649445

Davidson GR, Bennett SJ, Beard WC, et al. (2005) Trace elements in sediments of an aging reservoir in rural mississippi: potential for mobilization following dredging. *Water, Air, and Soil Pollution* 163(1): 281–292. DOI: 10.1007/s11270-005-0731-x

Dey P and Sarkar AK (2011) Revisiting indigenous farming knowledge of Jharkhand (India) for conservation of natural resources and combating climate change. Indian Journal of Traditional Knowledge 10(1): 71–79.

Diacono M and Montemurro F (2011) Long-term effects of organic amendments on soil fertility. In: Lichtfouse E, Hamelin M, Navarrete M, et al. (eds) *Sustainable Agriculture Volume 2*. Dordrecht: Springer Netherlands, pp. 761–786. DOI: 10.1007/978-94-007-0394-0_34

D'Odorico P, Davis KF, Rosa L, et al. (2018) The global food-energy-water nexus. *Reviews of Geophysics* 56(3): 456–531. DOI: 10.1029/2017RG000591

Donaldson S, Adlard B and JØ Odland (2016) Overview of human health in the Arctic: conclusions and recommendations. *International Journal of Circumpolar Health* 75(1): 33807. DOI: 10.3402/ijch.v75.33807

Donaldson SG, Van Oostdam J, Tikhonov C, et al. (2010) Environmental contaminants and human health in the Canadian Arctic. *Science of The Total Environment* 408(22): 5165–5234. DOI: 10.1016/j.scitotenv.2010.04.059

Dorava JM and Milner AM (2000) Role of lake regulation on glacier-fed rivers in enhancing salmon productivity: the Cook Inlet watershed, south-central Alaska, USA. *Hydrological Processes* 14: 3149–3159.

Dubnick A, Wadham J, Tranter M, et al. (2017) Trickle or treat: the dynamics of nutrient export from polar glaciers. *Hydrological Processes* 31(9): 1776–1789. DOI: 10.1002/hyp.11149

Edwards TM, Miller HD and Guillette LJ (2006) Water quality influences reproduction in female mosquitofish (*Gambusia holbrooki*) from Eight Florida Springs. *Environmental Health Perspectives* 114(Suppl 1): 69–75. DOI: 10.1289/ehp.8056

Engwa GA, Ferdinand PU, Nwalo FN, et al. (2019) Mechanism and health effects of heavy metal toxicity in humans. In: *Poisoning in the Modern World - New Tricks for an Old Dog?* London: IntechOpen.

EPA (2020). *EPA Annual Environmental Justice Progress Report FY 2020*. Available at: https://www.epa.gov/sites/default/files/2021-01/documents/2020_ej_report-final-web-v4.pdf

Erickson ML, Yager RM, Kauffman LJ, et al. (2019) Drinking water quality in the glacial aquifer system, northern USA. *Science of the Total Environment* 694: 133735. DOI: 10.1016/j.scitotenv.2019.133735

FAO I (2020) The state of food security and nutrition in the world 2020: transforming food systems for affordable healthy diets. In: *The State of Food Security and Nutrition in the World (SOFI) 2020*. Rome, Italy: FAO, IFAD, UNICEF, WFP and WHO. DOI: 10.4060/ca9692en

Faramarzi M, Khalili P, Zaremehrjardy M, et al. (2019) The cascade of uncertainties in agro-hydrological model projections: implications for future water-food nexus in snow-dominated regions. *AGU Fall Meeting Abstracts* 2019: H31M–1919.

Foereid B, Lehmann J and Major J (2011) Modeling black carbon degradation and movement in soil. *Plant and Soil* 345(1): 223–236. DOI: 10.1007/s11104-011-0773-3

Forbes B (2013) Cultural resilience of social-ecological systems in the Nenets and Yamal-Nenets Autonomous Okrugs, Russia: a focus on reindeer nomads of the tundra ecology and society. *The Resilience Alliance* 18(4): art36. DOI: 10.5751/ES-05791-180436

Fortner SK, Mark BG, McKenzie JM, et al. (2011) Elevated stream trace and minor element concentrations in the foreland of receding tropical glaciers. *Applied Geochemistry* 26(11): 1792–1801. DOI: 10.1016/j.apgeochem.2011.06.003

Gagnaire B, Adam-Guillermin C, Bouron A, et al. (2011) The effects of radionuclides on animal behavior. In: Whitacre DM (ed) *Reviews of Environmental Contamination and Toxicology Volume 210*. New York, NY: Springer, pp. 35–58. DOI: 10.1007/978-1-4419-7615-4_2

Golovnev AV and Osherenko G (2018) *Siberian Survival: The Nenets and Their Story*. Ithaca and London: Cornell University Press.

Guillen J, Baeza A, Salas A, et al. (2012) Deer as Biomonitors of Radioactive Contamination. In: Cahler AA and Marsten JP (eds) *Deer: Habitat, Behavior and Conservation*. New York, NY: Nova Science, pp. 97–118. Available at: http://site.ebrary.com/id/10682960 (accessed 11 February 2021).

Guittard A, Baraer M, McKenzie JM, et al. (2017) Trace-metal contamination in the glacierized Rio Santa watershed, Peru. *Environmental Monitoring and Assessment* 189(12): 649. DOI: 10.1007/s10661-017-6353-0

Guittard A, Baraer M, McKenzie JM, et al. (2020) Trace metal stream contamination in a post peak water context: lessons from the Cordillera Blanca, Peru. *ACS Earth and Space Chemistry* 4(4): 506–514. DOI: 10.1021/acsearthspacechem.9b00269

Guzzetti E, Sureda A, Tejada S, et al. (2018) Microplastic in marine organism: environmental and toxicological effects. *Environmental Toxicology and Pharmacology* 64: 164–171. DOI: 10.1016/j.etap.2018.10.009

Hale RC, Seeley ME, La Guardia MJ, et al. (2020) A global perspective on microplastics. *Journal of Geophysical Research: Oceans* 125(1): e2018JC014719. DOI: 10.1029/2018JC014719

Hansen B, Voutchkova DD, Sandersen PBE, et al. (2021) Assessment of complex subsurface redox structures for sustainable development of agriculture and the environment. *Environmental Research Letters* 16(2): 025007. DOI: 10.1088/1748-9326/abda6d

Harrison S, Kargel JS, Huggel C, et al. (2018) Climate change and the global pattern of moraine-dammed glacial lake outburst floods. *The Cryosphere* 12(4): 1195–1209. DOI: 10.5194/tc-12-1195-2018

Hegglin E and Huggel C (2008) An integrated assessment of vulnerability to glacial hazards. *Mountain Research and Development* 28(3): 299–309. DOI: 10.1659/mrd.0976

Hembrom S, Singh B, Gupta SK, et al. (2020) A comprehensive evaluation of heavy metal contamination in foodstuff and associated human health risk: a global perspective. In: Singh P, Singh RP and Srivastava V (eds) *Contemporary Environmental Issues and*

Challenges in Era of Climate Change. Singapore: Springer, pp. 33–63. DOI: 10.1007/978-981-32-9595-7_2

Hering JG, Maag S and Schnoor JL (2016) A call for synthesis of water research to achieve the sustainable development goals by 2030. *Environmental Science & Technology* 50(12): 6122–6123. DOI: 10.1021/acs.est.6b02598

Hock R, Jansson P and Braun LN (2005) Modelling the response of mountain glacier discharge to climate warming. In: Huber UM, Bugmann HKM and Reasoner MA (eds) *Global Change and Mountain Regions: An Overview of Current Knowledge*. Dordrecht: Springer Netherlands, pp. 243–252. DOI: 10.1007/1-4020-3508-X_25

Hodson AJ (2014) Understanding the dynamics of black carbon and associated contaminants in glacial systems: black carbon and associated contaminants in glacial systems. *Wiley Interdisciplinary Reviews: Water* 1(2): 141–149. DOI: 10.1002/wat2.1016

Hong GH, Baskaran M, Molaroni SM, et al. (2011) Anthropogenic and natural radionuclides in caribou and muskoxen in the Western Alaskan Arctic and marine fish in the Aleutian Islands in the first half of 2000s. *Science of The Total Environment* 409(19): 3638–3648. DOI: 10.1016/j.scitotenv.2011.06.044

Hoondert RPJ, Ragas AMJ and Hendriks AJ (2021) Simulating changes in polar bear subpopulation growth rate due to legacy persistent organic pollutants – temporal and spatial trends. *Science of the Total Environment* 754: 142380. DOI: 10.1016/j.scitotenv.2020.142380

Hovelsrud GK, Poppel B, van Oort B, et al. (2011) Arctic societies, cultures, and peoples in a changing cryosphere. *AMBIO* 40(1): 100–110. DOI: 10.1007/s13280-011-0219-4

Howells AP, Lewis SJ, Beard DB, et al. (2018) Water treatment residuals as soil amendments: examining element extractability, soil porewater concentrations and effects on earthworm behaviour and survival. *Ecotoxicology and Environmental Safety* 162: 334–340. DOI: 10.1016/j.ecoenv.2018.06.087

Hung H, Halsall C, Ball H, et al. (2022) Climate change influence on the levels and trends of persistent organic pollutants (POPs) and chemicals of emerging Arctic concern (CEACs) in the Arctic physical environment – a review. *Environmental Science: Processes & Impacts*. DOI: 10.1039/D1EM00485A

Huntington HP, Carey M, Apok C, et al. (2019) Climate change in context: putting people first in the Arctic. *Regional Environmental Change* 19(4): 1217–1223. DOI: 10.1007/s10113-019-01478-8

IPCC (2018) Global*Warming of 1.5°C. an IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate povert*. In: Masson-Delmotte V, Zhai P, Pörtner H.-O, et al. (eds). Available at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_Low_Res.pdf (accessed 14 April 2021).

Jennings SR, Dollhopf DJ and Inskeep WP (2000) Acid production from sulfide minerals using hydrogen peroxide weathering. *Applied Geochemistry* 15(2): 235–243. DOI: 10.1016/S0883-2927(99)00041-4

Jones KC (2021) Persistent organic pollutants (POPs) and related chemicals in the global environment: some personal reflections. *Environmental Science & Technology* 55(14): 9400–9412. DOI: 10.1021/acs.est.0c08093

Kallenborn R, Ottesen RT, Gabrielsen GW, et al. (2011) PCB on Svalbard. Available at: https://www.sysselmesteren.no/contentassets/9a8cf80ee4094bfd8c515631bb9191fe/pcb-on-svalbard—report-2011.pdf (accessed 8 August 2022).

Kaltenborn BP, Nellemann C, Vistnes II, et al. (2010) *High Mountain Glaciers and Climate Change: Challenges to Human Livelihoods and Adaptation*. Arendal, Norway" GRID-ArendalUNEP.

Kang J-H, Choi S-D, Park H, et al. (2009) Atmospheric deposition of persistent organic pollutants to the East Rongbuk Glacier in the Himalayas. *Science of the Total Environment* 408(1): 57–63. DOI: 10.1016/j.scitotenv.2009.09.015

Khovrychev MP, Mareev IY and Pomytkin VF (1994) Ability of microbial biomass to sorb radionuclides. *Microbiology* 63(1): 83–86.

Kirrane EF, Luben TJ, Benson A, et al. (2019) A systematic review of cardiovascular responses associated with ambient black carbon and fine particulate matter. *Environment International* 127: 305–316. DOI: 10.1016/j.envint.2019.02.027

Knauer K, Sobek A and Bucheli TD (2007) Reduced toxicity of diuron to the freshwater green alga Pseudokirchneriella subcapitata in the presence of black carbon. *Aquatic Toxicology* 83(2): 143–148. DOI: 10.1016/j.aquatox.2007.03.021

Konisky DM, Hughes L and Kaylor CH (2016) Extreme weather events and climate change concern. *Climatic Change* 134(4): 533–547. DOI: 10.1007/s10584-015-1555-3

Koppes MN and Montgomery DR (2009) The relative efficacy of fluvial and glacial erosion over modern to orogenic timescales. *Nature Geoscience* 2(9): 644–647. DOI: 10.1038/ngeo616

Kumar V, Kumar R, Singh J, et al. (2019) *Contaminants in Agriculture and Environment: Health Risks and Remediation*. Kankhal: Agriculture and Environmental Science Academy.

Kurttio P, Pukkala E, Ilus T, et al. (2010) Radiation doses from global fallout and cancer incidence among reindeer herders and Sami in Northern Finland. *Occupational and Environmental Medicine* 67(11): 737–743. DOI: 10.1136/oem.2009.048652

Lawson DE (1982) Mobilization, movement and deposition of active subaerial sediment flows, Matanuska Glacier, Alaska. *The Journal of Geology* 90(3): 279–300. DOI: 10.1086/628680

Lin W, Dai J, Liu R, et al. (2019) Integrated assessment of health risk and climate effects of black carbon in the Pearl River Delta region, China. *Environmental Research* 176: 108522. DOI: 10.1016/j.envres.2019.06.003

López-Moreno JI, Fontaneda S, Bazo J, et al. (2014) Recent glacier retreat and climate trends in Cordillera Huaytapallana, Peru. *Global and Planetary Change* 112: 1–11. DOI: 10.1016/j.gloplacha.2013.10.010

Maldonado M, Maldonado-Campo JA, Ortega H, et al. (2011) Biodiversity in aquatic systems of the tropical Andes. In: Herzog SK, Martinez R, Jørgensenet PM et al. (eds), *Climate Change and Biodiversity in the Tropical Andes. IAI - Inter-American Institute for Global Change Research*, pp. 276–294. https://www1.bio.ku.dk/english/staff/?pure=en%2Fpublications%2Fbiodiversity-in-aquatic-systems-of-the-tropical-andes(63e252ae-84f9-4196-a1af-9d08291ebfb4).html

Manara A (2012) Plant responses to heavy metal toxicity. In: Furini A (ed) *Plants and Heavy Metals. SpringerBriefs in Molecular Science*. Dordrecht: Springer Netherlands, pp. 27–53. DOI: 10.1007/978-94-007-4441-7_2

Mark BG, French A, Baraer M, et al. (2017) Glacier loss and hydro-social risks in the Peruvian Andes. *Global and Planetary Change* 159: 61–76. DOI: 10.1016/j.gloplacha.2017.10.003

Marr P, Winkler S and Löffler J (2022) Environmental and socio-economic consequences of recent mountain glacier fluctuations in Norway. In: Schickhoff U, Singh RB and Mal S (eds) *Mountain Landscapes in Transition : Effects of Land Use and Climate Change*. Cham: Springer International Publishing, pp. 289–314. DOI: 10.1007/978-3-030-70238-0_10

McGovern M, Warner NA, Borgå K, et al. (2022) Is glacial meltwater a secondary source of legacy contaminants to arctic coastal food webs? *Environmental Science & Technology* 56(10): 6337–6348. DOI: 10.1021/acs.est.1c07062

McGregor D, Whitaker S and Sritharan M (2020) Indigenous environmental justice and sustainability. *Current Opinion in Environmental Sustainability* 43: 35–40. DOI: 10.1016/j.cosust.2020.01.007

Mead EL, Gittelsohn J, Roache C, et al. (2013) A community-based, environmental chronic disease prevention intervention to improve healthy eating psychosocial factors and behaviors in Indigenous Populations in the Canadian Arctic. *Health Education & Behavior* 40(5): 592–602. DOI: 10.1177/1090198112467793

Mernild SH, Beckerman AP, Yde JC, et al. (2015) Mass loss and imbalance of glaciers along the Andes Cordillera to the sub-Antarctic islands. *Global and Planetary Change* 133: 109–119. DOI: 10.1016/j.gloplacha.2015.08.009

Meza FJ, Vicuna S, Gironás J, et al. (2015) Water–food–energy nexus in Chile: the challenges due to global change in different regional contexts. *Water International* 40(5–6): 839–855. DOI: 10.1080/02508060.2015.1087797

Milner AM, Khamis K, Battin TJ, et al. (2017) Glacier shrinkage driving global changes in downstream systems. *Proceedings of the National Academy of Sciences* 114(37): 9770–9778. DOI: 10.1073/pnas.1619807114

Miner KR, Bogdal C, Pavlova P, et al. (2018) Quantitative screening level assessment of human risk from PCBs released in glacial meltwater: Silvretta Glacier, Swiss Alps. *Ecotoxicology and Environmental Safety* 166: 251–258. DOI: 10.1016/j.ecoenv.2018.09.066

Momblanch A, Papadimitriou L, Jain SK, et al. (2019) Untangling the water-food-energy-environment nexus for global change adaptation in a complex Himalayan water resource system. *Science of The Total Environment* 655: 35–47. DOI: 10.1016/j.scitotenv.2018.11.045

Mora M, Walker TR and Willis R (2022) *Multiple Contaminant Ecological Risk Evaluation in Small Craft Harbour Sediments in Nova Scotia, Canada. ID 4043618, SSRN Scholarly Paper, 25 February*. Rochester, NY: Social Science Research Network. DOI: 10.2139/ssrn.4043618

Nelson MK and Shilling D (2018) *Traditional Ecological Knowledge: Learning from Indigenous Practices for Environmental Sustainability*. Cambridge, New York, Melbourne, New Delhi, Singapore : Cambridge University Press.

Ness TM and Munkejord MC (2021) Being connected to nature, reindeer, and family: findings from a photovoice study on well-being among older South Sámi people. *International Journal of Circumpolar Health* 80(1): 1936971. DOI: 10.1080/22423982.2021.1936971

Nie S, Gao W, Chen Y, et al. (2009) Review of current status and research approaches to nitrogen pollution in Farmlands. *Agricultural Sciences in China* 8(7): 843–849. DOI: 10.1016/S1671-2927(08)60286-2

Nuttall M (2018) Arctic environments and peoples. In: *The International Encyclopedia of Anthropology*. New Jersey: American Cancer Society, pp. 1–7. DOI: 10.1002/9781118924396.wbiea1480

Nuttall M (2021) Arctic ecology, indigenous peoples and environmental governance. *Arctic Ecology* 1: 409–422. DOI: 10.1002/9781118846582.ch15

Offenberg JH and Baker JE (2002) The influence of aerosol size and organic carbon content on gas/particle partitioning of polycyclic aromatic hydrocarbons (PAHs). *Atmospheric Environment* 36(7): 1205–1220. DOI: 10.1016/S1352-2310(01)00427-7

Österlin C (2020) *Nature Conservation, Landscape Change and Indigenous Rights : The Role of Sámi Reindeer Herding for Environmental Objectives in the Swedish Mountain Landscape*. Department of Physical Geography, Stockholm University. Available at: http://urn.kb.se/resolve?urn=urn:nbn:se:su:diva-184776 (accessed 14 August 2021).

Overeem I, Hudson BD, Syvitski JPM, et al. (2017) Substantial export of suspended sediment to the global oceans from glacial erosion in Greenland. *Nature Geoscience* 10(11): 859–863. DOI: 10.1038/ngeo3046

Owen LA (1991) Mass movement deposits in the Karakoram Mountains: their sedimentary characteristics, recognition and role in Karakoram landform evolution. *Zeitschrift für Geomorphologie* 35: 401–424. DOI: 10.1127/zfg/35/1991/401

Owens PN, Blake WH and Millward GE (2019) Extreme levels of fallout radionuclides and other contaminants in glacial sediment (cryoconite) and implications for downstream aquatic ecosystems. *Scientific Reports* 9(1): 12531. DOI: 10.1038/s41598-019-48873-z

Pant RR, Zhang F, Rehman FU, et al. (2020) Spatiotemporal characterization of dissolved trace elements in the Gandaki River, Central Himalaya Nepal. *Journal of Hazardous Materials* 389: 121913. DOI: 10.1016/j.jhazmat.2019.121913

Poveda G, Espinoza JC, Zuluaga MD, et al. (2020) High impact weather events in the andes. *Frontiers in Earth Science* 8: 162. DOI: 10.3389/feart.2020.00162

Pralong MR, Turowski JM, Rickenmann D, et al. (2015) Climate change impacts on bedload transport in alpine drainage basins with hydropower exploitation. *Earth Surface Processes and Landforms* 40(12): 1587–1599. DOI: 10.1002/esp.3737

Prata JC, da Costa JP, Lopes I, et al. (2019) Effects of microplastics on microalgae populations: a critical review. *Science of The Total Environment* 665: 400–405. DOI: 10.1016/j.scitotenv.2019.02.132

Pratt DL and Fonstad TA (2017) Geochemical modelling of livestock mortality leachate transport through the subsurface. *Biosystems Engineering* 162: 67–80. DOI: 10.1016/j.biosystemseng.2017.08.002

Pritchard HD (2017) Asia's glaciers are a regionally important buffer against drought. *Nature* 545(7653): 169–174. DOI: 10.1038/nature22062

Prosekov AY and Ivanova SA (2018) Food security: the challenge of the present. *Geoforum* 91: 73–77. DOI: 10.1016/j.geoforum.2018.02.030

Rajković M, Stojanović MD, Pantelić GK, et al. (2006) Determination of strontium in drinking water and consequences of radioactive elements present in drinking water for human health. *Journal of*

Agricultural Sciences 51(1): 87–97. DOI: 10.2298/JAS0601087R

Ramakrishnan B, Maddela NR, Venkateswarlu K, et al. (2021) Organic farming: does it contribute to contaminant-free produce and ensure food safety? *Science of the Total Environment* 769: 145079. DOI: 10.1016/j.scitotenv.2021.145079

Rasul G (2014) Food, water, and energy security in South Asia: a nexus perspective from the Hindu Kush Himalayan region☆. *Environmental Science & Policy* 39: 35–48. DOI: 10.1016/j.envsci.2014.01.010

Rowan AV, Quincey DJ, Gibson MJ, et al. (2018) The sustainability of water resources in High Mountain Asia in the context of recent and future glacier change. *Geological Society of London* 462(1): 189–204. DOI: 10.1144/SP462.12

Rummukainen M (2012) Changes in climate and weather extremes in the 21st century. *WIREs Climate Change* 3(2): 115–129. DOI: 10.1002/wcc.160

Ryder S, Powlen K, Laituri M, et al. (2021) *Environmental Justice in the Anthropocene: From (Un)Just Presents to Just Futures*. London: Routledge.

Saaristo M, Brodin T, Balshine S, et al. (2018) Direct and indirect effects of chemical contaminants on the behaviour, ecology and evolution of wildlife. *Proceedings of the Royal Society B: Biological Sciences* 285(1885): 20181297. DOI: 10.1098/rspb.2018.1297

Scanlon BR, Ruddell BL, Reed PM, et al. (2017) The food-energy-water nexus: transforming science for society. *Water Resources Research* 53(5): 3550–3556. DOI: 10.1002/2017WR020889

Schriks M, Heringa MB, van der Kooi MME, et al. (2010) Toxicological relevance of emerging contaminants for drinking water quality. *Water Research* 44(2): 461–476. DOI: 10.1016/j.watres.2009.08.023

Seehaus T, Malz P, Sommer C, et al. (2019) Changes of the tropical glaciers throughout Peru between 2000 and 2016 – mass balance and area fluctuations. *The Cryosphere* 13(10): 2537–2556. DOI: 10.5194/tc-13-2537-2019

Seeley ME, Song B, Passie R, et al. (2020) Microplastics affect sedimentary microbial communities and nitrogen cycling. *Nature Communications* 11(1): 2372. DOI: 10.1038/s41467-020-16235-3

Shaw G and Bell JNB (1994) Plants and radionuclides. In: *Plants and the Chemical Elements*. Dordrecht: John Wiley & Sons, pp. 179–220. DOI: 10.1002/9783527615919.ch7

Shugar DH, Jacquemart M, Shean D, et al. (2021) A massive rock and ice avalanche caused the 2021 disaster at Chamoli, Indian Himalaya. *Science* 373(6552): 300–306. DOI: 10.1126/science.abh4455

Skuterud L and Thørring H (2012) Averted doses to norwegian sámi reindeer herders after the chernobyl accident. *Health Physics* 102(2): 208–216. DOI: 10.1097/HP.0b013e3182348e12

Skuterud L, Gaare E, Eikelmann IM, et al. (2005) Chernobyl radioactivity persists in reindeer. *Journal of Environmental Radioactivity* 83(2): 231–252. DOI: 10.1016/j.jenvrad.2005.04.008

Smith JL and Paul EA (1990) The significance of soil microbial biomass estimations. In: *Soil Biochemistry*. New York: Routledge.

Solgi E, Sheikhzadeh H and Solgi M (2018) Role of irrigation water, inorganic and organic fertilizers in soil and crop contamination by potentially hazardous elements in intensive farming systems: Case study from Moghan agro-industry, Iran. *Journal of Geochemical Exploration* 185: 74–80. DOI: 10.1016/j.gexplo.2017.11.008

Sommer C, Malz P, Seehaus TC, et al. (2020) Rapid glacier retreat and downwasting throughout the European Alps in the early 21st century. *Nature Communications* 11: 3209. DOI: 10.1038/s41467-020-16818-0

Staniszewska K, Cooke C and Reyes A (2020) Are melting alpine glaciers a source of legacy priority contaminants to downstream environments? *A High-Frequency Analysis of Water Chemistry in the Canadian Rockies* 22: 11516.

Steig EJ, Ding Q, Battisti DS, et al. (2012) Tropical forcing of Circumpolar Deep Water Inflow and outlet glacier thinning in the Amundsen Sea Embayment, West Antarctica. *Annals of Glaciology* 53(60): 19–28. DOI: 10.3189/2012AoG60A110

Stocki TJ, Gamberg M, Loseto L, et al. (2016) Measurements of cesium in Arctic beluga and caribou before and after the Fukushima accident of 2011. *Journal of Environmental Radioactivity* 162(163): 379–387. DOI: 10.1016/j.jenvrad.2016.05.023

Stott P (2016) How climate change affects extreme weather events. *Science* 352(6293): 1517–1518. DOI: 10.1126/science.aaf7271

Stott T and Convey P (2020) Seasonal hydrological and suspended sediment transport dynamics and their future modelling in the Orwell Glacier proglacial stream, Signy Island, Antarctica. *Antarctic Science* 33: 1–21. DOI: 10.1017/S0954102020000607

Strumness LA, Hooper RL and Mahoney JB (2004) Contaminant pathways and metal sequestration patterns in the lower coeur d'Alene River Valley, Idaho: Mechanics of Trace Metal Mobility. *AGU Spring Meeting Abstracts* 2004: H41E–04.

Suchanek TH (1994) Temperate coastal marine communities: biodiversity and threats. *American Zoologist* 34(1): 100–114. DOI: 10.1093/icb/34.1.100

Sunyer J (2008) The neurological effects of air pollution in children. *European Respiratory Journal* 32(3): 535–537. DOI: 10.1183/09031936.00073708

Sutton NB, Maphosa F, Morillo JA, et al. (2013) Impact of long-term diesel contamination on soil microbial community structure. *Applied and Environmental Microbiology* 79(2): 619–630. DOI: 10.1128/AEM.02747-12

Synnove JK, Björn A, Elaine B, et al. (2018) *The Andean Glacier and Water Atlas: The Impact of Glacier Retreat on Water Resources*. Paris and Arendal: UNESCO Publishing.

Taillant JD (2015) *Glaciers: The Politics of Ice*. New York: Oxford University Press.

Telling J, Anesio AM, Tranter M, et al. (2011) Nitrogen fixation on Arctic glaciers, Svalbard. *Journal of Geophysical Research: Biogeosciences* 116(G3): G03039. DOI: 10.1029/2010JG001632

Telling J, Stibal M, Anesio AM, et al. (2012) Microbial nitrogen cycling on the Greenland Ice Sheet. *Biogeosciences* 9(7): 2431–2442. DOI: 10.5194/bg-9-2431-2012

Terrapon-Pfaff J, Ortiz W, Dienst C, et al. (2018) Energising the WEF nexus to enhance sustainable development at local level. *Journal of Environmental Management* 223: 409–416. DOI: 10.1016/j.jenvman.2018.06.037

Tomar RS, Singh B and Jajoo A (2019) Effects of organic pollutants on photosynthesis. In: *Photosynthesis, Productivity and Environmental Stress*. Hoboken: John Wiley & Sons, pp. 1–26. DOI: 10.1002/9781119501800.ch1

Tovar-Sánchez E, Hernández-Plata I, SantoyoMartínez M, et al. (2018) Heavy metal pollution as a biodiversity threat. In: *Heavy Metals*. Rijeka: IntechOpen, pp. 383. DOI: 10.5772/intechopen.74052.

Tsosie R (2007) Indigenous people and environmental justice: the impact of climate change. *University of Colorado Law Review* 78: 1625.

Tsyplenkov A, Vanmaercke M, Golosov V, et al. (2020) Suspended sediment budget and intra-event sediment dynamics of a small glaciated mountainous catchment in the Northern Caucasus. *Journal of Soils and Sediments* 20(8): 3266–3281. DOI: 10.1007/s11368-020-02633-z

Van Der Velden S, Dempson JB, Evans MS, et al. (2013) Basal mercury concentrations and biomagnification rates in freshwater and marine food webs: Effects on Arctic charr (Salvelinus alpinus) from eastern Canada. *Science of the Total Environment* 444: 531–542. DOI: 10.1016/j.scitotenv.2012.11.099

Van Tiel M, Van Loon AF, Seibert J, et al. (2021) Hydrological response to warm and dry weather: do glaciers compensate? *Hydrology and Earth System Sciences* 25(6): 3245–3265. DOI: 10.5194/hess-25-3245-2021

Vandekerkhove E, Bertrand S, Torrejón F, et al. (2021) Signature of modern glacial lake outburst floods in fjord sediments (Baker River, southern Chile). *Sedimentology* 68(6): 2798–2819. DOI: 10.1111/sed.12874

Veettil BK and Simões JC (2019) The 2015/16 El Niño-related glacier changes in the tropical Andes. *Frontiers of Earth Science* 13(2): 422–429. DOI: 10.1007/s11707-018-0738-4

Veettil BK, Wang S, Florêncio de Souza S, et al. (2017) Glacier monitoring and glacier-climate interactions in the tropical Andes: a review. *Journal of South American Earth Sciences* 77: 218–246. DOI: 10.1016/j.jsames.2017.04.009

Veh G, Lützow N, Kharlamova V, et al. (2022) Trends, breaks, and biases in the frequency of reported glacier lake outburst floods. *Earth's Future* 10(3): e2021EF002426. DOI: 10.1029/2021EF002426

Vergara W, Deeb A, Leino I, et al. (2011) *Assessment of the Impacts of Climate Change on Mountain Hydrology : Development of a Methodology through a Case Study in the Andes of Peru*. Washington, DC: World Bank. DOI: 10.1596/978-0-8213-8662-0

Viviroli D, Archer DR, Buytaert W, et al. (2011) Climate change and mountain water resources: overview and recommendations for research, management and policy. *Hydrology and Earth System Sciences* 15(2): 471–504. DOI: 10.5194/hess-15-471-2011. DOI:

Vorkamp K and Rigét FF (2014) A review of new and current-use contaminants in the Arctic environment: Evidence of long-range transport and indications of bioaccumulation. *Chemosphere* 111: 379–395. DOI: 10.1016/j.chemosphere.2014.04.019

Wahlang B (2018) Exposure to persistent organic pollutants: impact on women's health. *Reviews on Environmental Health* 33(4): 331–348. DOI: 10.1515/reveh-2018-0018

Walker-Crawford N (2021) The moral climate of melting glaciers. In: *The Anthroposcene of Weather and Climate: Ethnographic Contributions to the Climate Change Debate*. New York: Berghahn Books, pp. 146–168.

Wang L, Bao S, Liu X, et al. (2021a) Low-dose exposure to black carbon significantly increase lung injury of cadmium by promoting cellular apoptosis. *Ecotoxicology and Environmental Safety* 224: 112703. DOI: 10.1016/j.ecoenv.2021.112703

Wang Y, Fu B and Liu Y (2021b) The water, food, energy, and ecosystem nexus in the Asian Alpine Belt: Research progress and future directions for achieving sustainable development goals. *Progress in Physical Geography: Earth and Environment* 45(5): 789–801. DOI: 10.1177/03091333211024540

White C and Gadd GM (1990) Biosorption of radionuclides by fungal biomass. *Journal of Chemical Technology & Biotechnology* 49(4): 331–343. DOI: 10.1002/jctb.280490406

WHO (2008) *Guidelines for drinking-water quality*. 3rd etition. Available at: https://www.who.int/water_sanitation_health/dwq/fulltext.pdf (accessed 8 June 2021).

Wilhelmsson D, Thompson RC, Holmström K, et al. (2013) Chapter 6 - marine pollution. In: Noone KJ, Sumaila UR and Diaz RJ (eds) *Managing Ocean Environments in a Changing Climate*. Boston: Elsevier, pp. 127–169. DOI: 10.1016/B978-0-12-407668-6.00006-9

Wilson NJ, Mutter E, Inkster J, et al. (2018) Community-based monitoring as the practice of indigenous governance: a case study of indigenous-led water quality monitoring in the Yukon River Basin. *Journal of Environmental Management* 210: 290–298. DOI: 10.1016/j.jenvman.2018.01.020

Witus AE, Branecky CM, Anderson JB, et al. (2014) Meltwater intensive glacial retreat in polar environments and investigation of associated sediments: example from Pine Island Bay, West Antarctica. *Quaternary Science Reviews* 85: 99–118. DOI: 10.1016/j.quascirev.2013.11.021

Wright SL, Thompson RC and Galloway TS (2013) The physical impacts of microplastics on marine organisms: a review. *Environmental Pollution* 178: 483–492. DOI: 10.1016/j.envpol.2013.02.031

Yao P, Wang J, Harbor JM, et al. (2020) The relative efficiency and influence of glacial and fluvial erosion on Tibetan Plateau landscapes. *Geomorphology* 352: 106988. DOI: 10.1016/j.geomorph.2019.106988

Yong CQY, Valiyaveettil S and Tang BL (2021) Toxicity of Microplastics and nanoplastics in mammalian systems. *International Journal of Environmental Research and Public Health* 17(5): 1509. DOI: 10.3390/ijerph17051509

Zainab I, Ali Z, Ahmad U, et al. (2022) Air contaminants and atmospheric black carbon association with white sky albedo at Hindukush Karakorum and Himalaya Glaciers. *Applied Sciences* 12(3): 962. DOI: 10.3390/app12030962

Zheng G, Allen SK, Bao A, et al. (2021) Increasing risk of glacial lake outburst floods from future Third Pole deglaciation. *Nature Climate Change* 11(5): 411–417. DOI: 10.1038/s41558-021-01028-3

Zhu T, Wang X, Lin H, et al. (2020) Accumulation of pollutants in proglacial lake sediments: impacts of glacial meltwater and anthropogenic activities. *Environmental Science & Technology* 54(13): 7901–7910. DOI: 10.1021/acs.est.0c01849