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GUEST EDITORIAL

Melting glaciers unlock hidden contaminants

Nearly 70% of the Earth's freshwater is frozen in glaciers, ice caps and permafrost in Antarctica, the Arctic, and high mountains like the Himalayas, Andes and Alps. The high mountain glaciers contribute significantly to water flow in the mountain valley rivers that sustain the livelihoods of millions of people in the mountain states and the plains downstream. Glaciers have silently retreated for the last several decades as global warming and climate change relentlessly march on. The thinning and retreat of glaciers alter their hydrological properties, affecting freshwater flow and water availability in the downstream valley areas. The magnitude of runoff from the high mountain glaciers is expected to vary in a changing climate scenario, affecting downstream water resources, especially during the dry seasons or years. As glaciers and icecaps worldwide melt, they release water into the downstream rivers, ultimately reaching the ocean, causing sea levels to rise, thereby submerging the low-lying coastal regions and islands, resulting in the loss of several populated coastal areas.

Although the snow-covered and glaciated areas have generally been considered pristine environments, recent studies have shown they can be storehouses for environmental pollutants washed from the atmosphere by snow or directly deposited onto the ice surface. The release of glacial meltwater acts as a secondary source of contamination in proglacial environments years after the initial source was active. Studies have shown that Arctic and Antarctic ice sheets contain high levels of pollutants transported thousands of kilometres before being dropped onto the ice and incorporated into glaciers. Discovery of potentially toxic organic compounds, acids, metals and radionuclides in the Arctic region coincided with the decade of maximum anthropogenic emissions in Europe, North America and the former USSR (Barrie *et al.*, *Sci. Total Environ.*, 1992, **122**, 1–74). Ice core records from the central Himalayas have also demonstrated that toxic metals attributed to the European Industrial Revolution dominated the past atmospheric contamination even on the top of the Himalayas (Gabrielli *et al.*, *PNAS*, 2020, **117**, 3967–3973). Located in the proximity of populated and increasingly industrializing Asian countries, the glaciers of the Himalayas continue to receive higher levels of atmospheric pollutants in recent times than other mountain glacier regions in the world. As a result, in addition to the impact on the downstream water budget, the melting of glaciers is a significant environmental and socio-economic issue, particularly in the Himalayan Mountain states.

Glaciers are not just masses of ice; they are teeming with life and are repositories of various microorganisms such as viruses, bacteria, fungi, algae and invertebrates. They also trap natural debris and anthropogenic contaminants transported through the air from nearby and remote regions. The anthropogenic contamination detected in glacial and proglacial environments includes black carbon, fallout radionuclides, potentially toxic elements, microplastics, nitrogen-based contaminants and persistent organic pollutants (Beard *et al.*, *Prog. Phys. Geogr.*, 2022, **46**, 630–648). Human activities, such as industrialization, mining and agricultural practices, release contaminants into the environment, which are transported to high mountain regions through long-range atmospheric transport. As glaciers steadily melt, they release the nutrients and pollutants accumulated through several decades into water bodies, which can further affect the downstream ecosystems.

The highest concentration of pollutants is found within the cryoconite holes. Cryoconite holes are water-filled holes on the surface of a glacier caused by enhanced ice melt around trapped sediment (Takeuchi, *Ann. Glaciol.*, 2002, **34**, 409–414). Cryoconite is a dark powdery dust made of tiny rock particles, soot and microbes, which is deposited and builds up on snow, glaciers, or ice caps. They are dynamic sites for cycling organic matter, nutrients and elements in otherwise dry and desiccating glacier surface environments (Samui *et al.*, *Ann. Glaciol.*, 2018, **59**, 69–76). Cryoconites form when photosynthetic cyanobacteria release sticky extracellular polymeric substances into the environment, which aggregate mineral dust, microorganisms and organic matter into granules. Heterotrophic bacteria colonize these granules, progressively darkening them through the formation of humic substances due to bacterial decomposition of organic matter. The dark colour makes the cryoconite granules absorb more sunlight, melting the ice and forming holes in the ice surface. These cryoconite holes deepen over time, creating small pools of water that can act as reservoirs for anthropogenic contaminants. One of the primary contaminants that accumulates in cryoconite holes is black carbon, a product of incomplete combustion from vehicle exhaust and brown carbon aerosols from crop burning and forest fires. Black carbon imparts black and grey colour to the ice, which absorbs more sunlight than the surrounding white or blue ice, causing it to melt more quickly and increasing the rate of glacial retreat. The enhanced melting, in turn, can lead to the release of legacy contaminants, bacteria and viruses trapped in the ice, creating a feedback loop that exacerbates the impact of anthropogenic activity on the environment.

Microplastics are now found in virtually every environment on Earth, including the oceans, rivers and air. Recent studies have shown that microplastics are also present in the Himalayan glaciers and can be transported downstream through meltwater, potentially contaminating the water supply of millions of people (Talukdar *et al*., *Sci. Total Environ.*, 2023, **874**, 162495). Cryoconite holes accumulate significant concentrations of pesticides (Ferrario *et al*., *Environ. Pollut.*, 2017, **230**, 919–926) and persistent organic pollutants such as polychlorinated biphenyls and polycyclic aromatic hydrocarbons (Weiland-Bräuer *et al*., *Front. Microbiol.*, 2017, **8**, 1105). They are found in high levels in cryoconite holes in the Himalayan glaciers close to human settlements, tourist camps and agricultural activities. The presence of these pollutants has resulted in the selection of specialized bacteria capable of metabolizing them (Weiland-Bräuer *et al*., *Front. Microbiol.*, 2017, **8**, 1105). Contamination by anthropogenic antibiotics has also resulted in the accumulation of antibiotic-resistant bacteria in cryoconite holes (Makowska *et al*., *Sci. Total Environ.*, 2020, **716**, 137022). With an increase in the ice-melting rate in recent years, a considerable number of these microorganisms are released during summer from cryospheric environments and enter ecosystems close to human settlements. As some of these microbes and viruses are potentially pathogenic, there is a growing concern that the release of ice-entrapped microbes could lead to local epidemics.

In addition to organic pollutants, cryoconite holes can also hold heavy metals such as arsenic, lead, cadmium and mercury, which are environmentally toxic at high concentrations. While these harmful elements can have natural origins like weathering of rocks and volcanic eruptions, human activities such as mining and industrial processes are potentially dominant sources.

Cryoconite granules also accumulate Fallout Radionuclides (FRNs) resulting from natural and artificial sources, such as cosmic radiation, nuclear weapons testing, and nuclear accidents, such as the ones that occurred in Chernobyl and Fukushima. FRNs have been detected in many regions of the global cryosphere, with cryoconite sediment containing some of the highest concentrations of radionuclides, especially ^{137}Cs, ^{241}Am and ^{210}Pb (Owens *et al*., *Sci. Rep.*, 2019, **9**, 1–9). These radionuclide concentrations can reach levels comparable to those recorded in highly contaminated areas near nuclear disaster sites. The activity of ^{137}Cs in cryoconite, especially in European glaciers, has exceeded safe levels established by the World Health Organization. While ^{137}Cs is decreasing in the environment due to its half-life of ~30 years, others produced due to the decay of their parent radionuclides are increasing in the background. Therefore, FRNs will persist in the environment for multiple generations, impacting the ecosystem and the health of the people and animals living in the surrounding areas. Even low to moderate levels of FRNs found in drinking water have been shown to increase the risk of cancer and genetic malformations (WHO, 2008).

Contaminants in cryoconite holes accumulate due to scavenging by cryoconite of colloidal and dissolved materials in the meltwater. Cryoconite comprises fine particles (like clays and silts) and organic material (including extracellular polymeric substances), which have high binding capacities for FRNs, trace metals and nutrients. Since most Himalayan glaciers are associated with proglacial lakes that keep expanding as the glaciers are retreating, it is possible that the sediments accumulating in these lakes could contain elevated levels of contaminants and thus pose a risk to aquatic life and human health in downstream ecosystems, especially in communities that rely on glacier-fed rivers for drinking water. Exposure to persistent organic pollutants, heavy metals and other contaminants can lead to various health hazards, including cancer, reproductive disorders and developmental problems. Therefore, the potential health impacts of contaminants accumulating in the cryosphere are of particular concern in the context of climate change and glacier recession. As the glaciers continue to melt, the volume of water flowing through Himalayan rivers will increase, potentially exacerbating the risks associated with the contamination of various ecosystems. As discussed previously, glacier recession may also expose frozen contaminants from the past, releasing additional pollutants into the freshwater supply. Considering the continuity of glacier melt in a warming world and high concentrations of water-soluble emerging pollutants in cryosphere systems, the melting process will increase the risks of emerging contaminants to freshwater sources and should be of great concern. Therefore, understanding the biogeochemical cycling, ecology, and the accumulation of contaminants in unique systems like cryoconite holes and proglacial lakes in the high Himalayas is critical for assessing the potential impact of these pollutants on human health in the downstream environments. More research is required to address gaps in knowledge on areas of potential risk from releasing glacially stored legacy contaminants, the impacts of these contaminants on the ecosystem, and the health of humans and livelihoods. It is also essential to monitor the levels of pollutants in glaciers and cryoconite holes to assess the extent of the problem and to develop strategies for mitigating the impact of these contaminants on the environment and human health.

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