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Contribution of glaciers to water, energy and food security in mountain regions: current perspectives and future priorities

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Letter

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Abstract

Mountain glaciers are crucial sources of fresh water, contributing directly and indirectly to water, energy and food supplies for hundreds of millions of people. Assessing the impact of diminishing glacial meltwater contributions to the security of this resource is critical as we seek to manage and adapt to changing freshwater dynamics in a warming world. Both water quantity and quality influence water (in)security, so understanding the fluxes of water, sediment and contaminants through glacial and proglacial systems is required for holistic assessment of meltwater contribution to downstream resource security. In this paper we consider the socio-environmental role of and pressures on glacier-fed waters, discuss key research priorities for the assessment of both the quantity and quality of meltwater and reflect on the importance of situating our understanding within a transdisciplinary and inclusive research landscape.

Introduction

Glaciers are a key component of many of the world's mountain 'water towers', which support ~1.9 billion people living in or downstream of mountain areas (Immerzeel and others, 2020). Recent studies using satellite records show high rates of glacial mass loss, which have accelerated over the last few decades (Hugonnet and others, 2021). While this is a global phenomenon, there are strong regional variations, reflecting local atmospheric and topographic conditions. Importantly, these spatial variations mean that there are also regional differences in downstream impacts, with some of the most populated areas and vulnerable ecosystems most at risk, including parts of Arctic Canada and Russia, Asia, Europe and North and South America. In many of these areas, both ecosystem functions and the livelihoods of local peoples are reliant on a consistent supply of meltwater and the delivery of associated sediment and nutrients. Thus, glacial meltwater can be viewed as a source of vital ecosystem services, underpinning resource security, wellbeing and environmental function (Fig. 1; Cook and others, 2021). Numerous species of fish are reliant on the timely flow of cold and clean water, while in the case of human populations, many regions of the planet are reliant on glacier meltwater for hydropower, drinking water and irrigation, among other requirements (Milner and others, 2017). While humans may be able to adapt to the rate of downstream change associated with glacial melt, in many situations ecosystem response is unlikely to be able to match this, and there are predictions of declining and shifting populations of both terrestrial and aquatic fauna particularly species specifically adapted to glacial conditions (Cauvy-Fraunié and Dangles, 2019). Similarly, decreases in glacier meltwater production, which is a transboundary challenge, may contribute to geopolitical instability (e.g. Karthe and others, 2015; Molden and others, 2017), particularly when twinned with water use and abstraction pressures from population and economic growth, and unsustainable land-use practices. This paper summarises the role of meltwater for downstream resources, the challenges of changing water quantity and quality, and key future research priorities in this field.

Quantity and quality of glacier-fed waters

Water security means having sustainable access to water of sufficient quantity and quality in order to support socio-economic development and human and ecosystem wellbeing. A key concept for assessing long-term water security is *peak water*, which in the context of glaciers describes the point in time where meltwater-derived runoff reaches its maximum under conditions of negative mass balance, resulting in a subsequent reduction of glacier contribution to streamflow. Huss and Hock (2018) conducted a global-scale modelling assessment of peak water in 56 large, glaciated catchments, estimating that peak water had already passed in

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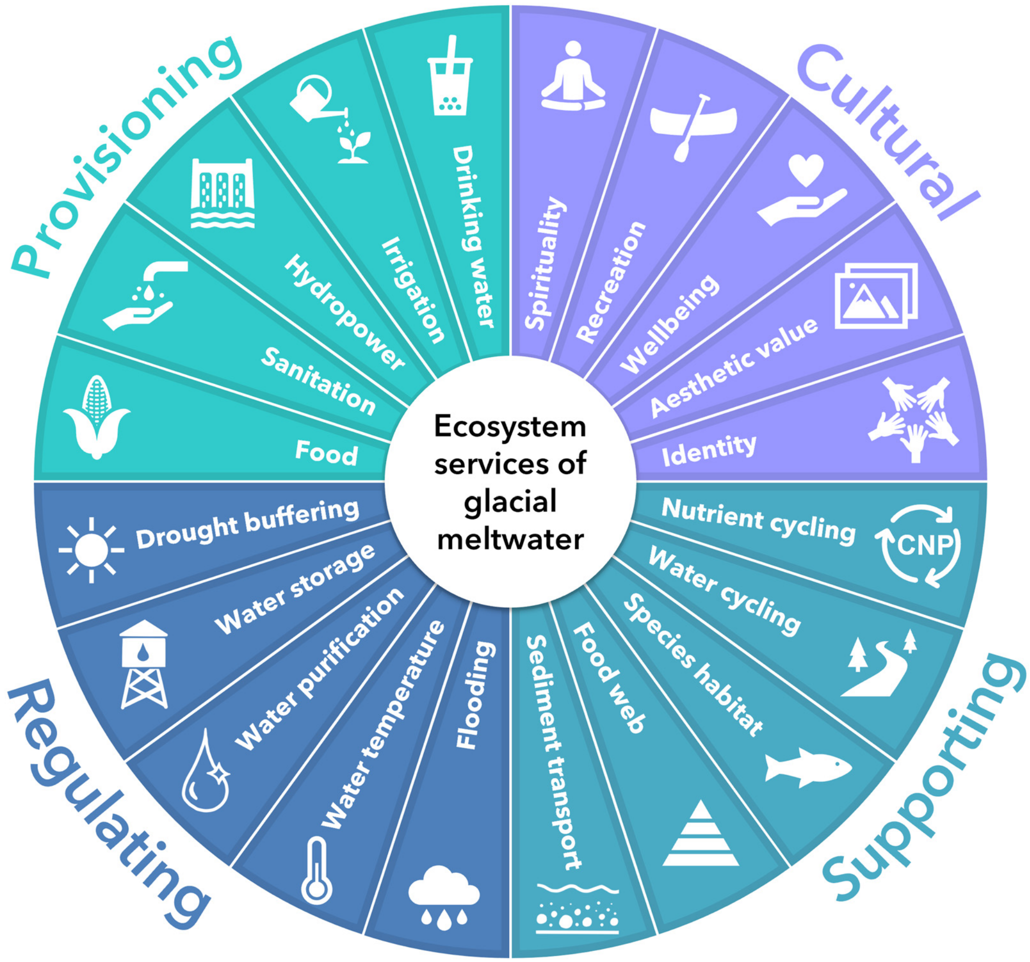

Fig. 1. Examples of the cultural, provisioning, regulating, and supporting ecosystem services provided by glacial meltwater in mountain regions.

45% of the catchments by 2017. The study found that while in many smaller catchments in areas like the Andes and European Alps peak water has either already passed or is predicted to in the next decade, some catchments in High Mountain Asia may see an increase in glacier runoff contribution until the middle of the century. Although a current problem for areas where peak water has passed, this difference in the timing of peak water may allow for the design of management and adaptation strategies *before* it is reached in other regions. Peak water can be estimated based on modelling or on observations of river discharge, but precisely *where* discharge is measured can impact estimations. For example, using a discharge record at a location distal (e.g. 10 km) to a glacier will decrease the proportion of meltwater contribution to discharge in comparison to other sources, and reflect any human abstraction before that point. Similarly, the temporal extent of discharge observations (e.g. a few years vs decades; continuous vs seasonal) can also influence the timing of when peak water is predicted.

An important consideration for both peak water estimation and water security assessment more broadly is whether we look at discharge on an annual, seasonal, or event-scale basis. The extent to which meltwater contributes to river discharge can vary considerably throughout the year, and meltwater can be a significant buffer to water supplies during periods of low rainfall in regions with a dry season or during drought (Ultee and others, 2022). Regional climate events such as the El Niño Southern Oscillation can place further pressure on water security through drought intensification, or conversely lead to extreme precipitation events (Cai and others, 2020). Extreme El Niño Events (EENE) have also been demonstrated to lead to an increase in suspended sediment yields in rivers of the Peruvian Andes, with sediment accumulated in mountain areas during normal, drier years rapidly mobilised by high rainfall and river capacity during EENE (Morera and others, 2017). Understanding overall glacier contribution to streamflow in comparison to contributions from snowmelt, precipitation, and groundwater, and how this changes over time, is also crucial for assessing the capacity of glaciers to buffer water supplies (Van Tiel and others, 2021).

In addition to assessing water quantity, recent research on the accumulation of anthropogenic contaminants on glaciers, and within downstream proglacial waters and sediments, has highlighted a need for renewed focus on the environmental quality of glacier-fed catchments (e.g. Ferrario and others, 2017). Glaciers act as temporary repositories for natural and anthropogenic atmospherically transported materials, in addition to materials from more local sources. This includes contaminants such as metals and trace elements, persistent organic pollutants (POPs), fallout radionuclides (FRNs), and black carbon (Beard and others, 2022), with a number of volatile organic compounds, including POPs, preferentially accumulated in polar and alpine regions through cold condensation (Pawlak and others, 2021). Some of these contaminant classes have been shown to pose a threat to ecosystem health in other settings, for example FRNs, which have now been reported in multiple regions of the mountain cryosphere including Scandinavia and the Alps (e.g. Baccolo and others, 2020; Clason and others, 2021). Mercury (Hg) is a contaminant of concern as it can be found in higher trophic levels of the food web, with Arctic rivers shown to be a significant Hg source to ocean waters, posing potential health risks for communities that rely on marine fauna as a food source (Hawkings and others, 2021). Mountain regions such as the Tibetan Plateau have also been identified as sources of Hg to downstream ecosystems (e.g. Sun and others, 2017), highlighting a need for improved understanding of Hg biogeochemical cycling and bioavailability.

Sediment plays a central role in governing water quality and availability, and can in its own right be viewed as a contaminant via physical issues such as increased turbidity and clogging of fish-spawning habitats. Sediment provides an important ecosystem service for aquatic species and for the cycling of nutrients, but it can also transport and accumulate contaminant elements, in addition to posing a threat to hydropower and ecosystems through excess sediment generation and transport (Owens, 2020). Glaciers are a significant contributor to the production of new sediment, and studies have demonstrated that glaciated high-alpine areas can be responsible for disproportionately higher sediment fluxes than lower-lying regions (Schmidt and others, 2022). Glacier retreat and erosion can also foster chemical and physical weathering of local rock, promoting oxidation and in some cases acid rock drainage which can impact downstream water acidity and toxicity in regions such as Peru's Cordillera Blanca (Santofimia and others, 2017). Furthermore, changes in glacial meltwater production also impact water temperature, a key water quality indicator, resulting in increased vulnerability of alpine river ecosystems for which even small changes in water temperature can be a major stressor (Michel and others, 2020).

Resource security and sustainability in mountain glacier regions

Water is perhaps the most exploited of natural resources, yet plays a crucial role in the security of other resources central to human wellbeing. The water–energy–food (WEF) security nexus describes the interdependence of three key resources, and the nexus approach promotes synergy in policy and management implementation across sectors (Heal and others, 2021). The WEF nexus is an important concept for mountain regions, where meltwater can be a major annual or seasonal contributor not only to domestic water supplies but also for agricultural and hydropower production. However, both the mountain environment and the social dynamics of the regions within which glaciers sit can pose considerable challenges for WEF security, through environmental and climatic change, loco-regional hazards, and socio-economic pressures including overconsumption (Fig. 2). Meanwhile, the global population living under water scarcity has increased sixteenfold over the last 100 years (Kummu and others, 2016).

Meltwater from both glaciers and snow is a crucial source for irrigation in regions including the Andes and South Asia. For example, in the Indus River basin, which supports a large population and produces food supplies for many more, meltwater accounts for 40% of water abstracted for irrigation each year (Lutz and others, 2022). Many mountain regions are seeing a transition from snow-dominant to rain-dominant precipitation, which can lead to short-term increases in discharge, especially in winter or monsoon periods, but lower storage capacity to buffer reduced discharge in drier periods (Laurent and others, 2020). Furthermore, shifts in the timing of melt onset and peaks are not always in-step with peak demand (Lutz and others, 2022). Hydropower provides most of the world's renewable energy, and in many regions it is the main source of electricity. In the case of British Columbia, Canada, hydropower is responsible for nearly 90% of the province's electricity, much of which is supplied by glacial meltwater (Canada Energy Regulator, 2022). The European Alps and High Mountain Asia are also reliant on meltwater as a contributor to hydropower generation, however in areas like Switzerland that contribution is projected to decrease by the mid-century (Schaefli and others, 2019), while lakes used for hydropower are also at risk from natural hazards. Glacial lakes are a common feature of glaciated mountain environments, yet they can be prone to glacial lake outburst floods (GLOFs), often triggered by mass movements and landscape destabilisation (Li and others, 2022). GLOFs pose a threat to both human life and infrastructure, including hydropower generation, but in regions like the Himalayas hydropower projects are being pushed into catchment headwaters where GLOF peak discharge may be greater and uncertainties around flood risk are higher (Schwanghart and others, 2016).

While ultimately there is an urgent need for global mitigation of climate change to reduce impacts felt at the local scale, there is also an important role for loco-regional solutions to both water quantity and quality issues. The use of tech solutions as local strategies for glacier conservation can be applied where financially viable, often when glaciers are used as an economic service such as for skiing. However, these strategies, such as ice surface albedo modification and snow generation, are costly in terms of money and time, and are limited both spatially and temporally in the impact they have for loco-regional mass balance (Carver and Tweed, 2021). Strategies for adapting to changing meltwater supplies at catchment-scale are also being trialled, including the construction of ice stupas, first introduced in Ladakh, which provide a source of water at times when discharge is otherwise low. The eco-hydrological function of wetlands in mountain regions is another potential solution, as wetlands can act as natural reservoirs to buffer downstream water supplies, while also providing a water purification service (Santofimia and others, 2017; Valois and others, 2020). At management level, market-based instruments such as payment for ecosystem services (PES) schemes can be used, so that beneficiaries of water services financially reward landowners for taking actions that ensure the conservation of mountain ecosystems. However, the implementation of PES in certain Andean territories, for example, can face highly disruptive social processes, and inclusion of key stakeholders is paramount to ensuring that PES schemes are legitimate and sustainable (Dextre and others, 2022).

Future research priorities

The current nature of water (in)security in glacier-fed catchments means that improved understanding of meltwater contribution to downstream resources must be a priority for future research (Fig. 3). As discussed above, research design for how we measure or model meltwater contribution to river runoff can include a range of spatial and temporal scales, thus, being clear in our communication of how we assess meltwater contribution is crucial if we are to successfully feed into water policy and management strategies. The quality of glacial meltwater and the proglacial environment have been somewhat neglected in comparison to studies of melt generation, yet both contaminant accumulation and sediment flux can play a crucial role in the availability of that water for domestic supplies, energy generation, and food production. Future research may look to integrate both quantity and quality for overall assessment of water security in mountain glacier catchments, including monitoring of meltwater for legacy and emerging contaminants, such as microplastics and perfluoroalkyl substances (e.g. MacInnis and others, 2021; Beard and others, 2022). Advances in remote sensing, particularly the temporal resolution of imagery and increased use of active sensors, may offer an avenue for improved spatio-temporal water monitoring and assessment, as we have seen for other areas of glaciological research (Taylor and others, 2021). Glacier mass balance

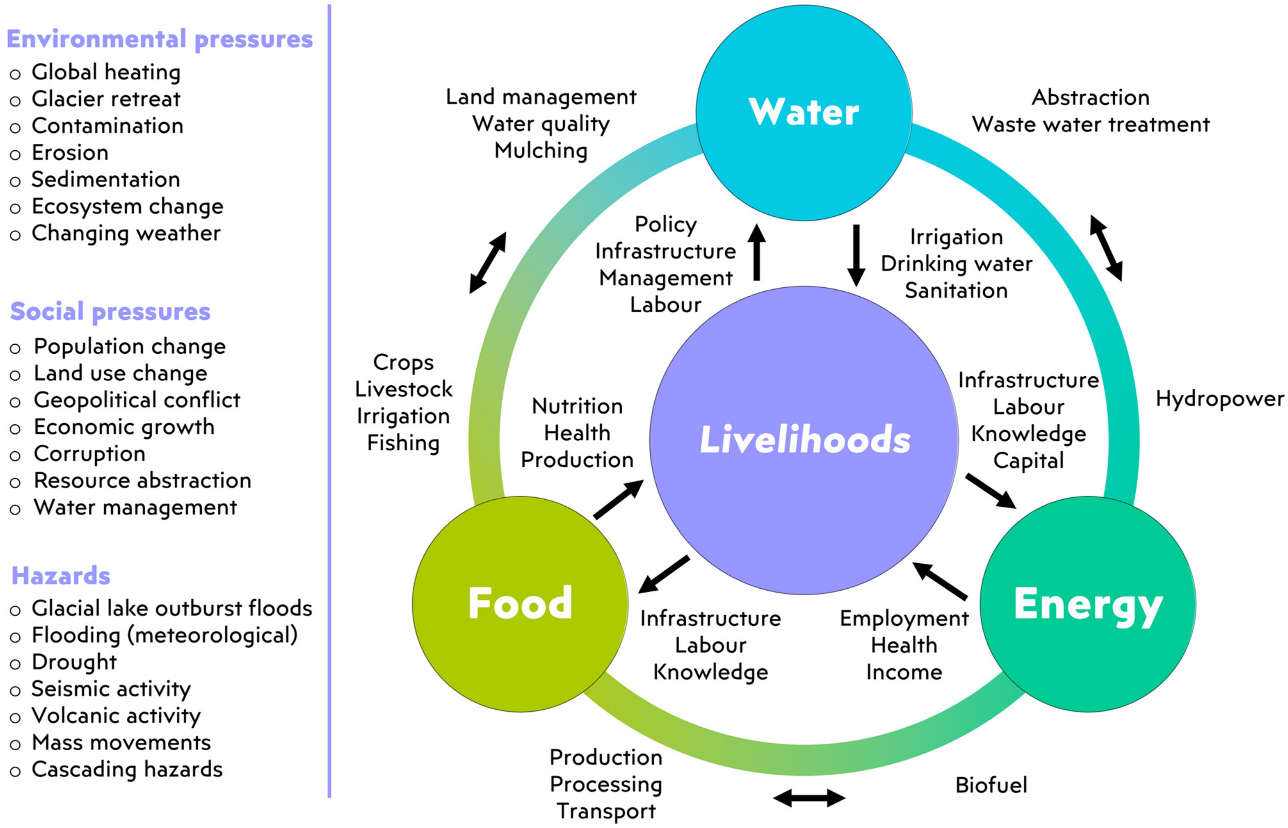

Fig. 2. Socio-environmental relationships within the WEF security nexus and how the nexus is interlinked with livelihoods. Examples of environmental pressures, social pressures, and hazards that can threaten the security and sustainability of the nexus in mountain glacier regions are also described.

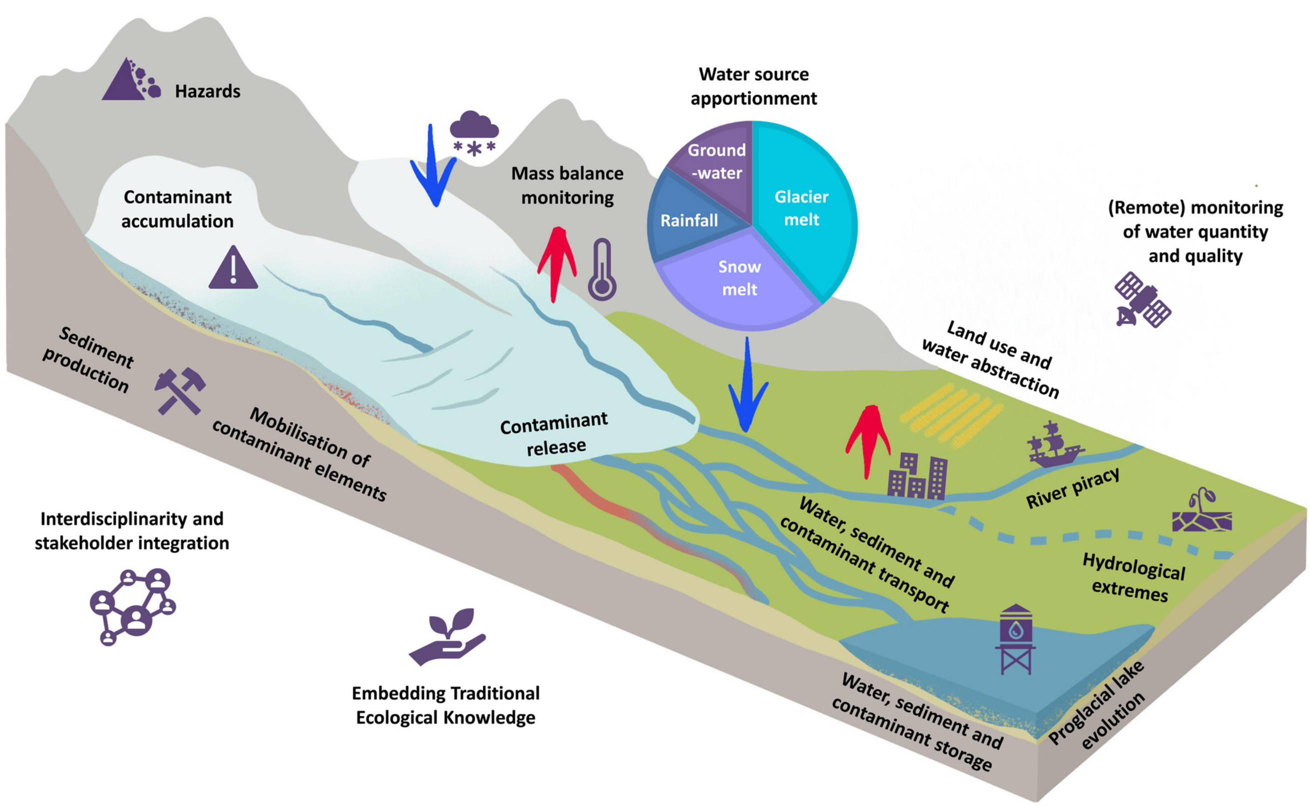

Fig. 3. Research priorities for assessment of water security in mountain glacier catchments.

has seen considerable advances in spatio-temporal coverage over the last ~20 years thanks to remote sensing (e.g. Hugonnet and others, 2021), while freshwater bodies are now routinely monitored for water quality, water temperature and spatial extent (e.g. European Space Agency Lakes Climate Change Initiative; Carrea and others, 2022).

Both remote sensing and modelling are reliant on ground-based observations to support robust predictions of future hydrological dynamics. In some regions of the mountain cryosphere there remains a dearth of observational data, particularly the hydro-meteorological data required for peak water identification and water security assessment. Thus, improved monetary and scientific support for extending observational records should be a priority. Furthermore, the integration of glaciers within common hydrological models remains limited, with models like the soil and water assessment tool, which is used regularly in catchment science to simulate water and sediment flux response to changing climate and land-use, often neglecting robust parameterisations of glacier cover (Omani and others, 2017) and associated energy balance. Similarly, very few studies have coupled glacier models with the variable infiltration capacity model, which simulates water and energy balances and can be used to assess land-use practices and reservoir management, among other applications (Zhao and others, 2013). Recent research has made strides towards better implementation of glacier mass balance and meltwater discharge within hydrological models (e.g. Eidhammer and others, 2021), but this coupling, particularly with regards to dynamical glacier evolution, remains in its infancy. As discussed more below, improved interdisciplinary collaboration within glacier-fed water resources research would lead not only to improvements in model integration, but also research outcomes and impact.

Mountain glaciers occupy dynamic environments, and the retreat of those glaciers can translate to changes to downstream hydrological configurations. For example, Shugar and others (2017) observed river piracy of the Slims River following accelerated retreat of Kaskawulsh Glacier, Yukon, Canada, whereby meltwater previously feeding the river was redirected into the Alsek River. The level of Kluane Lake also dropped following this redirection, while sediment transfer to the lake halted completely, with as yet poorly understood consequences for local ecology. This type of radical hydrological system reorganisation has rarely been observed in proglacial environments (see also Björnsson and others, 2011), however continued retreat of glaciers and evolution of dynamic proglacial systems should be a focus of future research given potential consequences for abrupt changes to local freshwater availability and management. Proglacial lake evolution is another example of dynamic change in deglaciating mountain environments, with the growth of existing lakes, and appearance of new ones, offering both opportunities for water supply and energy generation and risks relating to flooding and cascading hazards (Haeberli and others, 2016). In managing both the risk and resource potential of proglacial waters, upstream–downstream relationships should be an important consideration for future research and policy, recognising the impact of storage and abstraction for stakeholders in the upper and lower reaches of glaciated catchments (Drenkhan and others, 2022).

One of the most crucial priorities we identify for future research in this field is improved integration of social science and other physical sciences with glaciological research, so that findings transcend disciplines and can more readily generate impact. Water-related issues are complex, and we argue that these issues are best tackled from an interdisciplinary and transdisciplinary perspective, including through the generation of datasets that cross traditional disciplinary boundaries and apply methodologies that synthesise quantitative and qualitative data in a meaningful way (e.g. Richter and others, 2022). Additionally, it is important to recognise both the opportunities *and* barriers to collaborative interdisciplinary research to enable research design and communication strategies that speak across disciplines and between researchers and participants (Rangecroft and others, 2020). While research design has the potential to embed these considerations, interdisciplinarity needs to be better supported by funders so that research outcomes more often translate to impact. Without stepping out of disciplinary silos we are unlikely to reach the full potential of research into glacier-fed waters. Furthermore, data must be open and accessible to other communities of researchers and stakeholders, not only in terms of where that data are stored, but also in how data and metadata are described.

Finally, there is a continued need to integrate Traditional Ecological Knowledge (TEK) in assessment of glacier-fed water availability, in order to understand the consequences of glacier retreat on resource security, communities, and ecological systems in a holistic way. Indigenous peoples are susceptible to the impacts of a changing cryosphere due to the historical injustices they have experienced, and the social, economic, and cultural consequences of environmental change, but are also inherently resilient to that change (Ford and others, 2020). By challenging and expanding what we view as ‘knowledge’, and better listening to indigenous accounts of natural events and change, TEK may also be recognised and embedded more fully in the generation of scientific knowledge and solutions to environmental challenges (Cruikshank, 2012). Additionally, co-design and co-creation of research *with* communities and stakeholders is a practice that could be used more commonly, and not simply as a research ‘add-on’. The co-production of knowledge has the potential to generate greater buy-in for water management schemes such as PES, promote community empowerment, and contribute to improved resilience of communities in mountain glacier regions. The effects of glacier retreat and changing meltwater production are already being felt for millions of people, so it is timely that collaborative understanding of mountain glacier change, and the knock-on impacts for resource security, should be a central focus of our future research efforts.

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References

Baccolo G and 14 others (2020) Cryoconite: an efficient accumulator of radioactive fallout in glacial environments. *The Cryosphere* **14**, 657–672. doi: 10.5194/tc-14-657-2020.

Beard D and 5 others (2022) Anthropogenic contaminants in glacial environments I: inputs and accumulation. *Progress in Physical Geography: Earth and Environment* **46**(4), 630–648. doi: 10.1177/03091333221107376.

Björnsson H, Jóhannesson T and Snorrason Á (2011) Recent climate change, projected impacts, and adaptation capacity in Iceland. In Linkov I and Bridges T (eds), *Climate. NATO Science for Peace and Security Series C: Environmental Security*. Dordrecht: Springer, 467–477. doi: 10.1007/978-94-007-1770-1_24.

Cai W and 22 others (2020) Climate impacts of the El Niño–Southern Oscillation on South America. *Nature Reviews Earth & Environment* **1**, 215–231. doi: 10.1038/s43017-020-0040-3.

Canada Energy Regulator (2022) https:cer-rec.gc.ca/en/data-analysis/energy-markets/provincial-territorial-energy-profiles/provincial-territorial-energy-profiles-british-columbia.html (Accessed 17 August 2022).

Carrea L and 16 others (2022) ESA lakes climate change initiative (Lakes_cci): lake products, version 2.0.2. NERC EDS Centre for Environmental Data Analysis, 6 July 2022. doi: 10.5285/a07deacaffb8453e93d57ee214676304.

Carver RE and Tweed FS (2021) Cover the ice or ski on grass? *Geography (Sheffield, England)* **106**(3), 116–127. doi: 10.1080/00167487.2021.1970926.

Cauvy-Fraunié S and Dangles O (2019) A global synthesis of biodiversity responses to glacier retreat. *Nature Ecology & Evolution* **3**, 1675–1685. doi: 10.1038/s41559-019-1042-8.

Clason C and 8 others (2021) Accumulation of legacy fallout radionuclides in cryoconite on Isfallsglaciären (Arctic Sweden) and their downstream spatial distribution. *The Cryosphere* **15**, 5151–5168. doi: 10.5194/tc-15-5151-2021.

Cook D, Malinauskaite L, Davíðsdóttir B and Ögmundardóttir H (2021) Co-production processes underpinning the ecosystem services of glaciers and adaptive management in the era of climate change. *Ecosystem Services* **50**, 101342. doi: 10.1016/j.ecoser.2021.101342.

Cruikshank J (2012) Are glaciers 'good to think with'? Recognising indigenous environmental knowledge. *Anthropological Forum* **22**(3), 239–250. doi: 10.1080/00664677.2012.707972.

Dextre RM and 6 others (2022) Payment for ecosystem services in Peru: assessing the socio-ecological dimension of water services in the upper Santa River basin. *Ecosystem Services* **56**, 101454. doi: 10.1016/j.ecoser.2022.101454.

Drenkhan F and 5 others (2022) Looking beyond glaciers to understand mountain water security. *Nature Sustainability* **6**, 130–138. doi: 10.1038/s41893-022-00996-4.

Eidhammer T and 9 others (2021) Mass balance and hydrological modeling of the Hardangerjøkulen Ice Cap in south-central Norway. *Hydrology and Earth System Sciences* **25**, 4275–4297. doi: 10.5194/hess-25-4275-2021.

Ferrario C, Finizio A and Villa S (2017) Legacy and emerging contaminants in meltwater of three Alpine glaciers. *Science of the Total Environment* **574**, 350–357. doi: 10.1016/j.scitotenv.2016.09.067.

Ford JD and 5 others (2020) The resilience of indigenous peoples to environmental change. *One Earth* **2**(6), 532–543. doi: 10.1016/j.oneear.2020.05.014.

Haeberli W and 5 others (2016) New lakes in deglaciating high-mountain regions – opportunities and risks. *Climatic Change* **139**, 201–214. doi: 10.1007/s10584-016-1771-5.

Hawkings JR and 21 others (2021) Large subglacial source of mercury from the southwestern margin of the Greenland ice sheet. *Nature Geoscience* **14**, 496–502. doi: 10.1038/s41561-021-00753-w.

Heal KV and 8 others (2021) Water quality: the missing dimension of water in the water–energy–food nexus. *Hydrological Sciences Journal* **66**(5), 745–758. doi: 10.1080/02626667.2020.1859114.

Hugonnet R and 10 others (2021) Accelerated global glacier mass loss in the early twenty-first century. *Nature* **592**, 726–731. doi: 10.1038/s41586-021-03436-z.

Huss M and Hock R (2018) Global-scale hydrological response to future glacier mass loss. *Nature Climate Change* **8**, 135–140. doi: 10.1038/s41558-017-0049-x.

Immerzeel WW and 31 others (2020) Importance and vulnerability of the world's water towers. *Nature* **577**, 364–369. doi: 10.1038/s41586-019-1822-y.

Karthe D, Chalov S and Borchardt D (2015) Water resources and their management in Central Asia in the early twenty first century: status, challenges and future prospects. *Environmental Earth Sciences* **73**, 487–499. doi: 10.1007/s12665-014-3789-1.

Kummu M and 8 others (2016) The world's road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability. *Scientific Reports* **6**, 38495. doi: 10.1038/srep38495.

Laurent L and 8 others (2020) The impact of climate change and glacier mass loss on the hydrology in the Mont-Blanc massif. *Scientific Reports* **10**, 10420. doi: 10.1038/s41598-020-67379-7.

Li D and 16 others (2022) High Mountain Asia hydropower systems threatened by climate-driven landscape instability. *Nature Geoscience* **15**, 520–530. doi: 10.1038/s41561-022-00953-y.

Lutz AF and 7 others (2022) South Asian agriculture increasingly dependent on meltwater and groundwater. *Nature Climate Change* **12**, 566–573. doi: 10.1038/s41558-022-01355-z.

MacInnis J and 6 others (2021) Investigation of perfluoroalkyl substances in proglacial rivers and permafrost seep in a high Arctic watershed. *Environmental Science: Processes & Impacts* **24**(1), 42–51. doi: 10.1039/D1EM00349F.

Michel A, Brauchli T, Lehning M, Schaefli B and Huwald H (2020) Stream temperature and discharge evolution in Switzerland over the last 50 years: annual and seasonal behaviour. *Hydrology and Earth System Sciences* **24**, 115–142. doi: 10.5194/hess-24-115-2020.

Milner AM and 16 others (2017) Glacier shrinkage driving global changes in downstream systems. *PNAS* **114**(37), 9770–9778. doi: 10.1073/pnas.1619807114.

Molden D and 5 others (2017) Advancing regional and transboundary cooperation in the conflict-prone Hindu Kush–Himalaya. *Mountain Research and Development* **37**(4), 502–508. doi: 10.1659/MRD-JOURNAL-D-17-00108.

Morera SB, Condom T, Crave A, Steer P and Guyot JL (2017) The impact of extreme El Niño events on modern sediment transport along the western Peruvian Andes (1968–2012). *Scientific Reports* **7**, 11947. doi: 10.1038/s41598-017-12220-x.

Omani N, Srinivasan R, Karthikeyan R and Smith PK (2017) Hydrological modeling of highly glacierized basins (Andes, Alps, and Central Asia). *Water* **9**(2), 111. doi: 10.3390/w9020111.

Owens PN (2020) Soil erosion and sediment dynamics in the Anthropocene: a review of human impacts during a period of rapid global environmental change. *Journal of Soils and Sediments* **20**, 4115–4143. doi: 10.1007/s11368-020-02815-9.

Pawlak F, Koziol K and Polkowska Z (2021) Chemical hazard in glacial melt? The glacial system as a secondary source of POPs (in the Northern Hemisphere). A systematic review. *Science of the Total Environment* **778**, 145244. doi: 10.1016/j.scitotenv.2021.145244.

Rangecroft S and 12 others (2020) Guiding principles for hydrologists conducting interdisciplinary research and fieldwork with participants. *Hydrological Sciences Journal* **65**(S2), 214–225. doi: 10.1080/02626667.2020.1852241.

Richter I and 16 others (2022) Building bridges between natural and social science disciplines: a standardized methodology to combine data on ecosystem quality trends. *Philosophical Transactions of the Royal Society B: Biological Sciences* **377**(1854), 20210487. doi: 0.1098/rstb.2021.0487.

Santofimia E, López-Pamo E, Palomino EJ, González-Toril E and Aguilera A (2017) Acid rock drainage in Nevado Pastoruri Glacier area (Huascarán National Park, Perú): hydrochemical and mineralogical characterization and associated environmental implications. *Environmental Science and Pollution Research* **24**, 25243–25259. doi: 10.1007/s11356-017-0093-0.

Schaefli B, Manso P, Fischer M, Huss M and Farinotti D (2019) The role of glacier retreat for Swiss hydropower production. *Renewable Energy* **132**, 615–627. doi: 0.1016/j.renene.2018.07.104.

Schmidt LK and 5 others (2022) Suspended sediment and discharge dynamics in a glaciated alpine environment: identifying crucial areas and time periods on several spatial and temporal scales in the Ötztal, Austria. *Earth Surface Dynamics* **10**, 653–669. doi: 10.5194/esurf-10-653-2022.

Schwanghart W, Worni R, Huggel C, Stoffel M and Korup O (2016) Uncertainty in the Himalayan energy–water nexus: estimating regional exposure to glacial lake outburst floods. *Environmental Research Letters* **11**, 074005. doi: 10.1088/1748-9326/11/7/074005.

Shugar DH and 6 others (2017) River piracy and drainage basin reorganization led by climate-driven glacier retreat. *Nature Geoscience* **10**, 370–375. doi: 10.1038/ngeo2932.

Sun X and 8 others (2017) The role of melting alpine glaciers in mercury export and transport: an intensive sampling campaign in the Qugaqie Basin, inland Tibetan Plateau. *Environmental Pollution* **220**(Part B), 936–945. doi: 10.1016/j.envpol.2016.10.079.

Taylor LS and 5 others (2021) Remote sensing of the mountain cryosphere: current capabilities and future opportunities for research. *Progress in Physical Geography: Earth and Environment* **45**(6), 931–964. doi: 10.1177/03091333211023690.

Ultee L, Coats S and Mackay J (2022) Glacial runoff buffers droughts through the 21st century. *Earth System Dynamics* **13**, 935–959. doi: 10.5194/esd-13-935-2022.

Valois R and 7 others (2020) Characterizing the water storage capacity and hydrological role of mountain peatlands in the arid Andes of north-central Chile. *Water* **12**(4), 1071. doi: 10.3390/w12041071.

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

Zhao Q and 8 others (2013) Coupling a glacier melt model to the variable infiltration capacity (VIC) model for hydrological modeling in north-western China. *Environmental Earth Sciences* **68**, 87–101. doi: 10.1007/s12665-012-1718-8.