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Review

Impacts of Loss of Cryosphere in the High Mountains of Northwest North America

John J. Clague [1,*] and Dan H. Shugar [2]

[1] Center for Natural Hazards Research, Department of Earth Sciences, Simon Fraser University, Burnaby, BC V6B 1R8, Canada
[2] Water, Sediment, Hazards, and Earth-Surface Dynamics (waterSHED) Lab, Department of Geoscience, University of Calgary, Calgary, AB T2N 1N4, Canada
* Correspondence: jclague@sfu.ca

Abstract: Global atmospheric warming is causing physical and biotic changes in Earth's high mountains at a rate that is likely unprecedented in the Holocene. We summarize changes in the presently glacierized mountains of northwest North America, including a rapid and large reduction in glacier ice and permafrost, a related increase in slope instability and landslides, river re-routing and other hydrological changes, and changing aquatic ecosystems. Atmospheric greenhouse gas concentrations continue to rise and will likely do so for at least the next several decades, if not longer, and mountains will continue to warm, perhaps reaching temperatures up to several degrees Celsius warmer than present over the remainder of this century. As a result, the rate of physical and biotic changes documented in this paper is very likely to dramatically increase and transform high-mountain environments.

Keywords: cryosphere; geohazards; river re-routing; sediment delivery; ecosystems; North America

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1. Introduction

Climate warming over the past century is global in scope, and its rate is unprecedented in the Holocene Epoch. Its magnitude and effects are particularly large at high latitudes and in high mountains, where it has caused large reductions in glaciers, ice sheets, sea ice, and permafrost [1–4]. About one-quarter of the rise in global sea level caused by the global shrinkage of glaciers over the past half century is believed to have come from glaciers bordering the Gulf of Alaska [5]. The deglaciation of Glacier Bay in Southeast Alaska, which began in the late 18th century, involved the loss of several thousand cubic kilometres of glacier ice [6], resulting in the highest uplift rates on Earth [7]. These losses are exceeded only by those at the end of the Pleistocene Epoch [8] and are expected to continue and perhaps accelerate through the remainder of this century [1,9–11].

Climate-driven reductions in the cryosphere are having significant physical impacts in mountains. High-mountain environments are especially sensitive to climate change because glacial, nival, and permafrost processes are temperature-dependent [6,12–15]. As glaciers and permafrost disappear, landslides and debris flows are becoming more common in mountains ranges around the world, including those in northwest North America [2,15–27]. Glacier thinning and retreat are also accompanied by glacial lake outburst floods that move large volumes of sediment and water downstream [28,29].

Climate warming in Earth's high mountains has also been a driver of downstream hydrological and ecological changes [2,10,30–40]. These changes have adversely impacted some organisms and forced others to adapt [33–35,38,40]. On the other hand, glacier retreat is opening up new habitats for some plants and animals [41,42].

In this paper, we examine the physical, hydrological, and ecological effects of the large-scale and rapid deglacierization of the high mountains of northwest North America. Our motivation is to better understand the linkages, interdependencies, and complexities of the processes induced by current and ongoing deglacierization. Although our study area is sparsely populated unlike, for example, the European Alps or the Himalayas, cryosphere loss in northwest North America carries a cascade of ecologically and societally important consequences.

We first provide examples of large-scale, climate-induced disruptions of rivers in the St. Elias Mountains and northern Coast Mountains of Alaska and Canada, and point to other watersheds where similar changes might happen later in this century. Next, we discuss the impacts of deglacierization on downstream sediment delivery and hydrology. Third, we consider the effects of deglacierization on ecosystems.

2. River Re-Routing Due to Deglacierization

An important effect of the growth and decay of ice sheets during the Pleistocene is the disruption and reorganization of rivers. The watersheds of the major river systems of Europe, Eurasia, and North America were strongly perturbed and shaped by Pleistocene ice sheets. Among them are the two largest watersheds in the Cordillera of northwest North America—the Yukon and Fraser watersheds. Prior to the Pleistocene, Yukon River flowed southward through Yukon Territory, rather than northward as it does today [43–45]. At the same time, Fraser River drained eastward through the Rocky Mountains, probably via the Peace River valley, whereas today it drains a watershed of some 220,000 km^2 and empties into an inland sea of the Pacific Ocean (Salish Sea) at Vancouver [46].

Watershed reorganization of the scale of that driven by the growth and decay of the large Pleistocene ice sheets is not possible today because these ice sheets no longer exist except in Greenland and Antarctica. However, it operates on a smaller scale in mountains that still support large amounts of glacier ice.

2.1. The 2016 Ä'äy Chú (Slims River) River Capture Event

The idea for this paper emerged from the 2016 Ä'äy Chú (formerly known as Slims River) capture event in Yukon, Canada. Over the past few hundred years, Kaskawulsh Glacier, one of the largest glaciers in the St. Elias Mountains, terminated at the divide separating the watershed of Alsek River from that of Yukon River (Figures 1 and 2). Historically, a large portion of Kaskawulsh Glacier meltwater flowed northward via Ä'äy Chú into Lhù'ààn Mân (Kluane Lake) and thence to Yukon River, reaching the Bering Sea more than 2400 km downstream. The remainder of the glacier's meltwater flowed southeast via Kaskawulsh River to Alsek River, which in turn flows to the Gulf of Alaska about 300 km downstream. Even though Kaskawulsh River has a much higher (steeper) gradient than Ä'äy Chú, it has been unable, during historic time, to capture all the meltwater flowing from Kaskawulsh Glacier because the glacier itself formed the barrier separating the two rivers at the drainage divide.

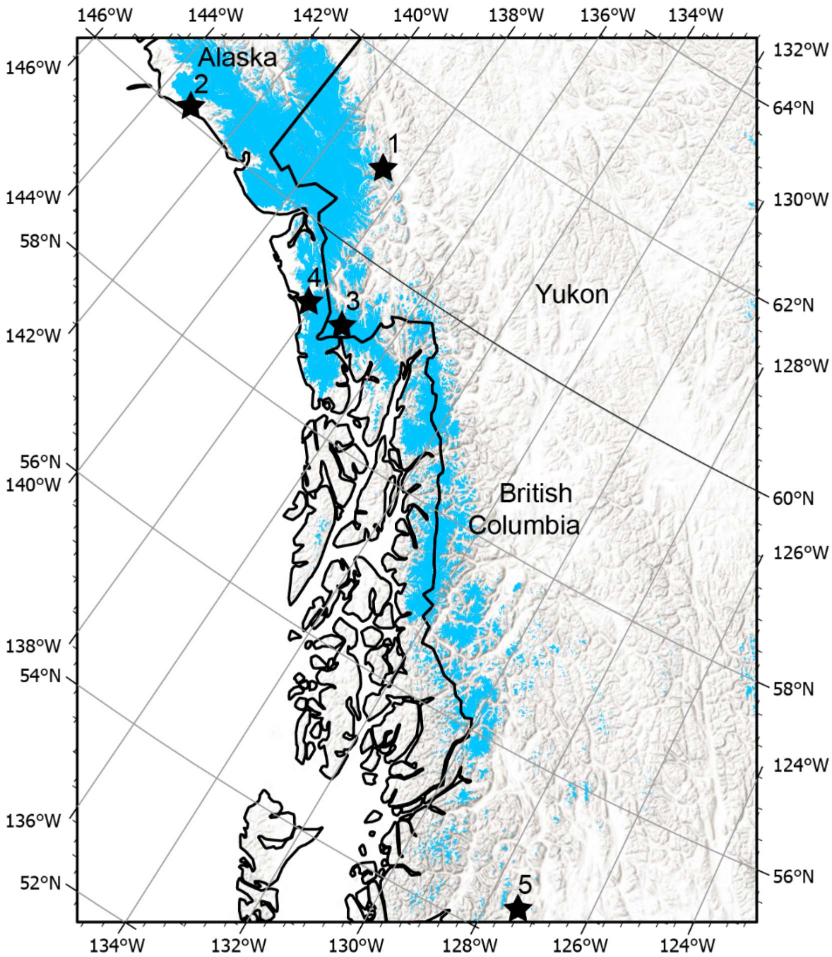

Figure 1. Map of northwest North America showing the locations of stream reorganization sites discussed in the text. (**1**) Kaskawulsh Glacier/Ä'äy Chú (Slims River); (**2**) Bering Glacier; (**3**) Melbern and Grand Pacific glaciers; (**4**) Alsek and Grand Plateau lakes; (**5**) Morice River Blue shaded area represents glacier cover from Randolf Glacier Inventory [47]. Projection is Canada Albers Equal Area Conic.

Figure 2. Satellite image showing drainage change at the terminus of Kaskawulsh Glacier between 2015 and 2016. The thin yellow arrow indicates the main meltwater discharge route prior to piracy. The path of Kaskawalsh River, which captured Ä'äy Chú, is indicated by the thick yellow arrow. Background image is an August 2021 satellite mosaic from Planet, and projection is Canada Albers Equal Area Conic.

In May 2016, set up by over a century of climate warming leading to the thinning and retreat of the terminus of Kaskawulsh Glacier, a proglacial lake ("Slims Lake") at the head of Ä'äy Chú drained via a channel through the glacier and into a lower lake at the head of Kaskawulsh River (Figure 2). The sudden emptying of Slims Lake cut off Ä'äy Chú from its source. Researchers have suggested that, barring a renewed advance of the glacier, which is unlikely to happen in a warming climate, the beheading of Ä'äy Chú is permanent [48]. Eventually, however, Kaskawulsh River will extend its watershed northward and capture all the water flowing into Kluane Lake, which is the largest body of water in Yukon. In the summer of 2016, the level of Kluane Lake fell about 1.7 m below normal and has remained low since then, creating safety issues related to boat launches at the shoreline and disruptions to traditional ways of life for the Lh'ùààn Mân Ku Dań (Kluane Lake People) [49]. Dust storms created by strong winds flowing off Kaskawulsh Glacier and down Ä'äy Chú Valley create visibility problems along the Alaska Highway at the south end of Kluane Lake [50]. The effects on the lake ecosystem are still being studied [51,52].

2.2. Future Drainage Reorganization Due to Glacier Retreat

There are many locations in the high mountains of northwest North America where drainage will be perturbed, and possibly re-routed, as glaciers continue to retreat. Lakes that are currently dammed by glacier ice will disappear and the meltwater that feeds them will take different routes. Here we provide a few examples among the many that we have identified during our field investigations and examination of satellite images.

2.2.1. Bering Glacier, Alaska

A lake dammed by an arm of Bering Glacier overtops a divide and drains to the southeast via Kosakuts and Kaliakh rivers (Figure 3). If Bering Glacier thins, as it likely will, the level of the lake will drop, ending flow to Kosakuts River. Eventually, water will flow out of the lake into another valley to the west.

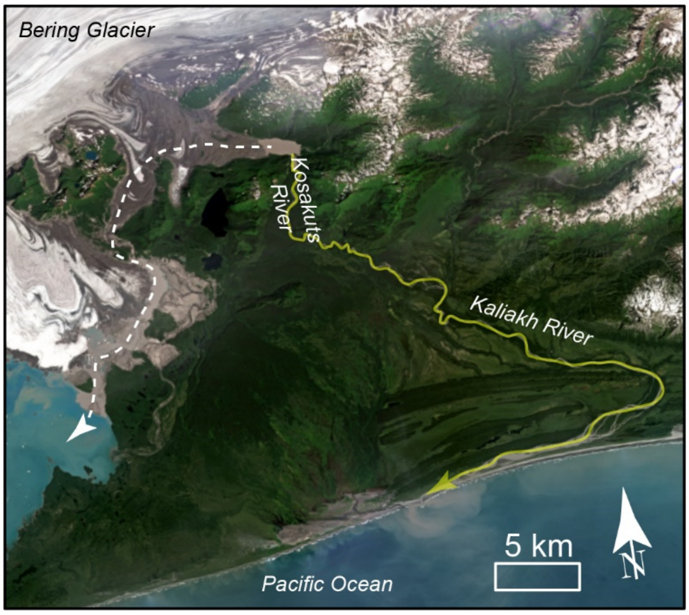

Figure 3. Satellite image showing a possible change in drainage at the southeast side of Bering Glacier. Yellow line shows the current drainage route; dashed white line indicates the possible future drainage path described in the text. Background image is a July 2021 satellite mosaic from Planet, and projection is Alaska Albers Equal Area Conic.

2.2.2. Grand Pacific and Melbern Glaciers, BC

Grand Pacific and Melbern glaciers, two of the largest valley glaciers in BC, have decreased over 50% in volume in the past few hundred years. Melbern Glacier has retreated 15 km during this period, accompanied by about 300–600 m of thinning [53]. More than half of the retreat has happened in recent decades. Retreat of the glacier has been accompanied by the formation of one of the largest ice-marginal lakes on Earth today, glacial Lake Melbern, which is now 20 km long and has an area of about 31.4 km^2 (Figures 4 and 5). Glacial Lake Melbern is impounded by Melbern and Grand Pacific glaciers in the south and bordered by an end moraine in the north. It presently discharges northward into Tatshenshini River just upstream of the latter's confluence with Alsek River. This route, however, may be ephemeral, as another steeper route exists, directly to Alsek River. The lower route might be taken if the moraine at the north end of Melbern Lake were to breach (Figure 4).

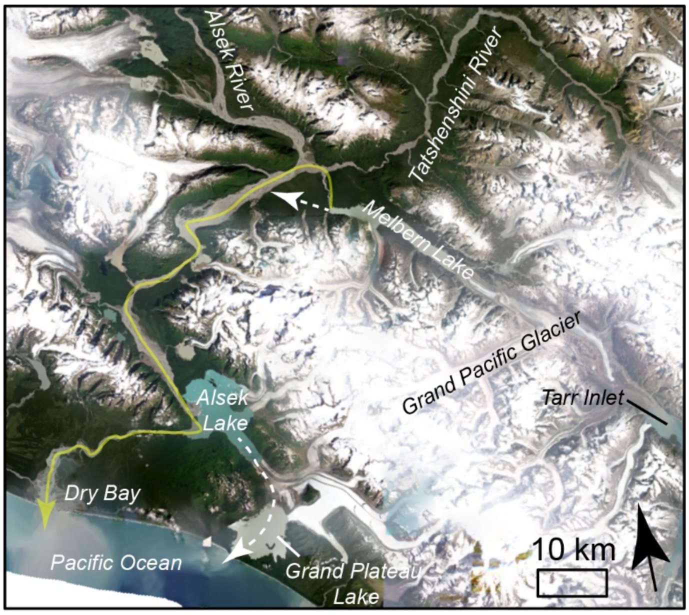

Figure 4. Satellite image mosaic of possible drainage changes in the lower Alsek River valley and Melbern valley. Yellow line shows the current drainage routes; dashed white lines indicate possible future drainage paths described in the text. Background image is an August 2021 satellite mosaic from Planet, and projection is Alaska Albers Equal Area Conic.

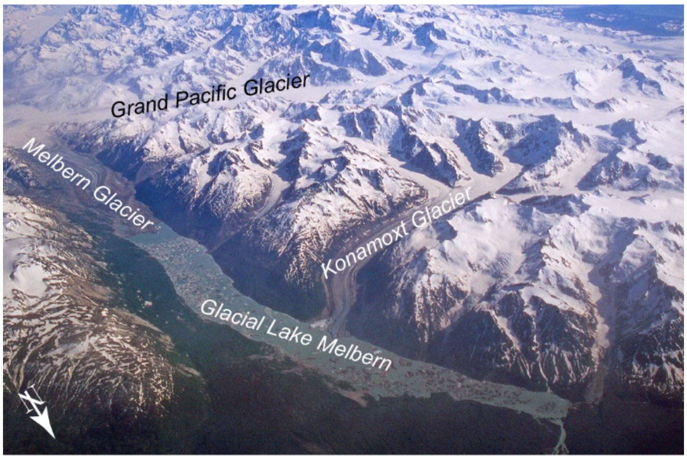

Figure 5. Glacial Lake Melbern, northwest British Columbia (compare with Figure 4). The lake is 20 km long and is impounded behind confluent Melbern and Grand Pacific glaciers northwest of Glacier Bay. An end moraine dams the lake at its north end. Photo by John Clague.

Another possible future scenario is that the dam formed by Melbern and Grand Pacific glaciers at the south end of Lake Melbern could fail, draining the lake and, as a consequence, opening a new fiord on Canada's west coast. This possibility is contingent on subglacial topography beneath the glaciers being low enough for water to drain south. Modeling work [54] and measurements of lake depth suggest that this is a distinct possibility. Grand Pacific Glacier, which terminates in Tarr Inlet at the BC–Alaska boundary (Figure 4), retreated 24 km between 1879 and 1912 [53]. As Grand Pacific and Melbern glaciers continue to retreat, the divide separating Tarr Inlet and the valley presently occupied by glacial Lake Melbern will become ice-free, potentially allowing the lake to empty into Glacier Bay.

2.2.3. Alsek Lake and Grand Plateau Glacier, Alaska

A river capture event may also happen in the future near the mouth of Alsek River. Alsek River makes an anomalous right-angle turn at Alsek Lake and flows 20 km west to Dry Bay (Figure 4). A more direct route to the Pacific Ocean is to the south, but this path is blocked by the north fork of Grand Plateau Glacier which, in that area, is grounded more than 400 m below sea level [55]. This glacier, however, is rapidly retreating due, in part, to the calving of its terminus in Alsek Lake and the unofficially named Grand Plateau Lake (Figure 6). The latter, which barely existed in the early 20th century [56,57], is now 9 km wide and has a surface area of about 74 km^2. Grand Plateau Lake currently has an area of 46 km^2, compared to only 5 km^2 in 1948. Laser altimetry shows that the terminus of Grand Plateau Glacier has thinned at rates of up to 10 m/yr in recent years [55].

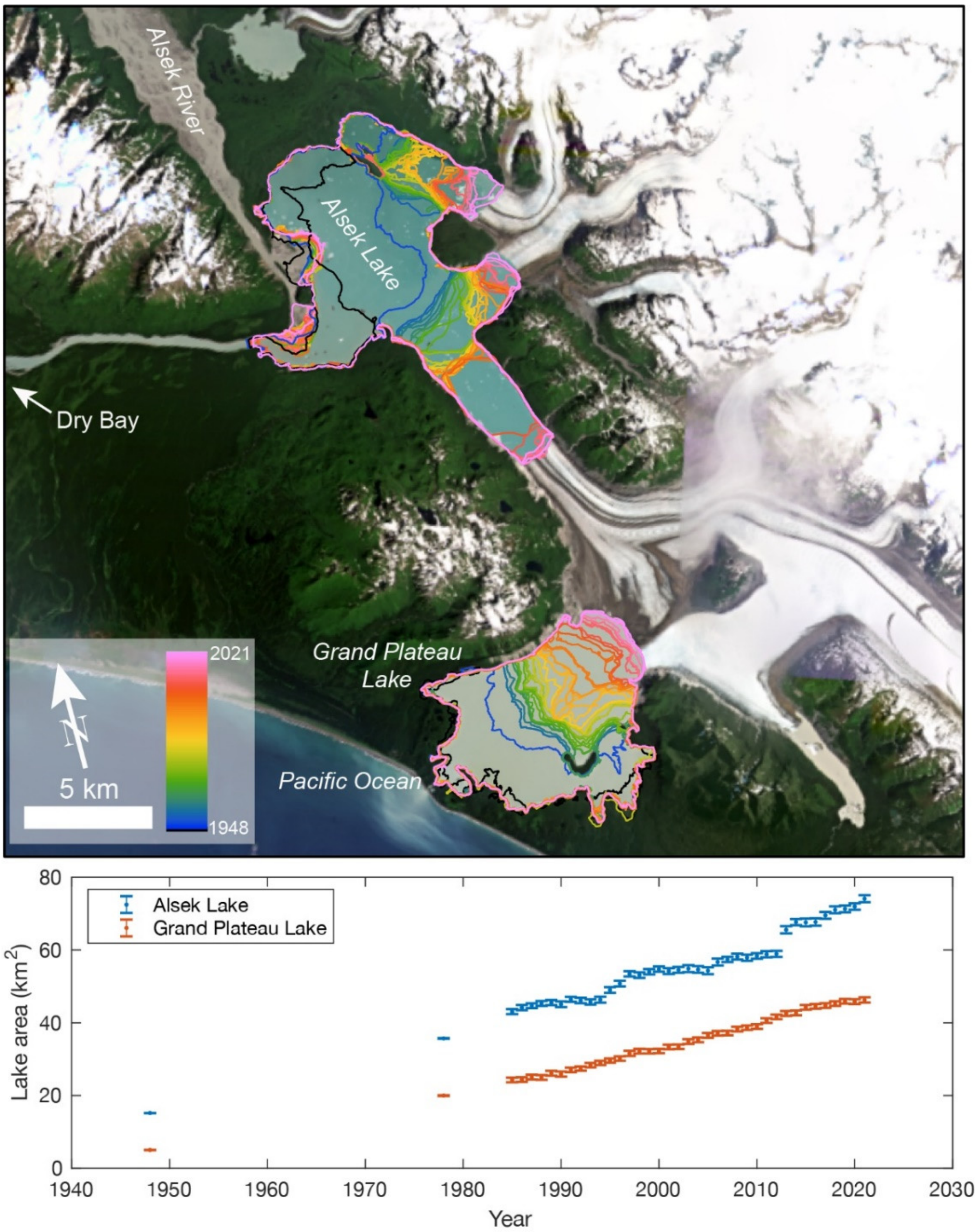

Figure 6. Recent growth of Grand Plateau and Alsek lakes, Alaska. Upper panel shows lake extents annually from 1985 to 2021 (from Landsat imagery), plus 1948 and 1978 (from georeferenced historic air photos). Background image is a July 2021 satellite mosaic from Planet and projection is Alaska Albers Equal Area Conic. Lower panel is time series of the lake areas. Error bars are per [58].

If Grand Plateau Glacier retreats another 7 km, Alsek River might abandon its current westerly path and flow directly south into the Pacific Ocean via Grand Plateau Lake, 30 km southeast of Dry Bay. Traditional and modern human activities centered on Dry Bay include commercial fishing, subsistence and sport hunting and fishing, and the terminus of a world-renowned rafting expedition. Under present management guidelines, these activities cannot be relocated to the predicted future outlet of Alsek River, which lies within federally designated wilderness of Glacier Bay National Park and Preserve.

3. Impacts of Deglacierization on Sediment Delivery and Hydrology

Drainage capture and diversion are only two of the effects of current deglacierization on glacier-fed rivers in northwest North America. Perhaps more important are the potential changes in sediment flux and possible changes in channel-forming flows that will likely accompany the loss of ice in the headwaters of these rivers.

Earlier onset of snowmelt in mountains has been accompanied by a greater proportion of winter precipitation falling as rain, which has altered annual hydrographs and, in some cases, has led to earlier spring runoff and a decrease in summer stream flows [37,59–68]. Although summer runoff from watersheds in heavily glacierized mountains continues to increase, peak summer runoff will likely decrease in many mountain ranges later in this century due to progressive reductions in snow and ice cover [9,69].

Glacierized areas have higher sediment yields than most unglaciated areas [70–72]. Slope failures and sediment mobilization linked to glacier recession and alpine permafrost thaw are likely to substantially increase erosion and sediment delivery to streams, at least over the short term [73–76]. However, there is still limited understanding of the effects of glacier recession on erosion and sediment production. Recent studies have adopted a landscape approach that emphasizes the importance of the connectivity of different areas within a catchment to decadal-scale changes in sediment production and delivery in attempts to quantify the catchment-scale response to glacier recession [13]. The time it will take for deglacierization to impact downstream hydrology and sediment yield depends on the connectivity of new sediment sources to the catchment drainage network [13,31,36,37,77,78]. If sediment is trapped in a proglacial lake or stored on floodplains, or if the capacity of the stream network is insufficient to transport the sediment, the lower watershed may show reduced sedimentary signals of deglacierization until proglacial lakes drain or lose accommodation space, or until an extreme event forces a widespread change to the landscape [13,14]. In deglacierizing watersheds with high connectivity between upland sediment sources and downstream sinks, greater sediment supply might be accompanied by increased braiding of channels, which would later decline as sediment supply wanes [79,80]. Overall, however, it is reasonable to expect increased sediment flux from rapidly deglacierizing and thawing watersheds over timescales of several decades [13,24,81].

Extreme precipitation and runoff events are important drivers of sediment mobilization and transport in northwest North America. High-intensity precipitation, rain-on-snow events, and outburst floods from glacier-, moraine-, and landslide-dammed lakes generate some of the largest hydrologic and sediment transport events on Earth (Figure 7) [82,83]. As glaciers thin and retreat and as alpine permafrost thaws, marginally stable rock slopes may fail, delivering increased amounts of rock debris to alpine valley bottoms.

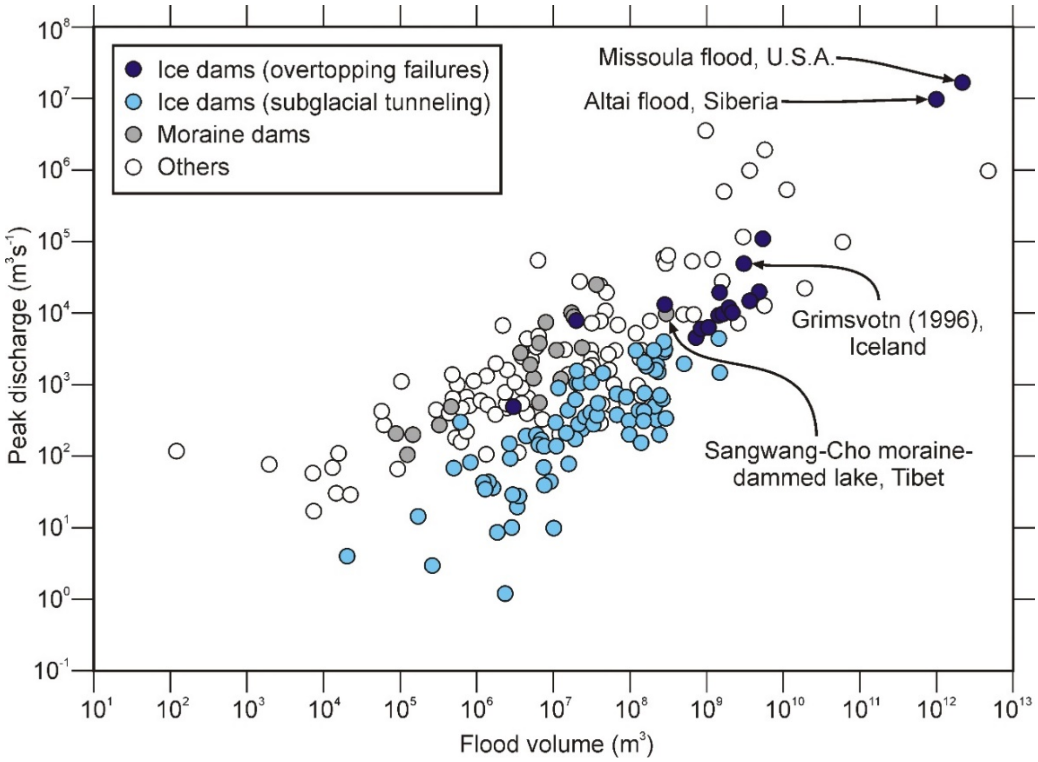

Figure 7. Outburst floods for which flood volume and peak discharge are known. The largest floods of each type are labeled. (From [28], Figure 14.1).

Researchers have argued that landslides and debris flows are becoming more common in deglaciating mountains ranges around the world, including those in northwest North America [2,14–27,73,84]. Slopes may be destabilized from thermal stresses on steep faces, thawing of permafrost, and perhaps increased storm rainfall.

Another consequence of the continuing deglaciation of high mountains is that many glacier-dammed lakes are draining suddenly and catastrophically, entraining and redepositing large amount of sediment and transforming valley floors downstream [28,29] (Figures 8 and 9). Glacier lake outburst floods may become more frequent in high mountains as new lakes form and existing ones grow [85,86]. Many glacier- and moraine-dammed lakes will be impacted by mass movements from adjacent destabilized mountain slopes [23,74,87].

Once deglaciation is complete, there will be a reduction in sediment delivery to alpine rivers and streams [88], but in the near future, that trend will be punctuated by extreme events that perturb the cycle, perhaps more frequently than in recent decades. This is, in effect, an episodically interrupted paraglacial cycle that plays out over a period of one or more centuries [89,90].

Changes during this transitional deglacierizing period are difficult to characterize and are subject to much uncertainty [81,91,92]. Sediment yields are likely to show annual to multi-decadal spikes as new sediment sources become available, but these spikes are idiosyncratic and subject to specific local conditions [93–95]. Conversely, coarse sediment delivery may be interrupted as glacial lakes form and trap sediment [96].

Figure 8. Floor of the west fork of Nostetuko River in the central Coast Mountains of British Columbia following the outburst flood from moraine-dammed Queen Bess Lake in August 1997. The floodwaters entrained and transported sediment on the valley floor and eroded the valley walls. This event has been documented by [97].

Figure 9. Top: Deeply eroded channel and fan of Elliot Creek following the outburst of Elliot Lake in the southern Coast Mountains of British Columbia (photos courtesy of Kat Pyne, Hakai Institute). A large rockslide entered the lake and generated a displacement wave that travelled 8 km down the valley to the fan where Elliot Creek enters Southgate River (lower photo). This event has been documented by [74].

Another approach to linking glacier recession and sediment production and delivery is empirical and field-based. Previous research on the impacts of the rapid reduction in glaciers in the Coast Mountains of British Columbia at the end of the Little Ice Age provide key insights into what can be expected in terms of channel-forming flows in many watersheds in northwest North America later in this century. Glacier cover in British Columbia increased during the climactic advances of the Little Ice Age in the eighteenth and nineteenth centuries [98]. As late as the late 1800s, alpine glaciers in the Coast Mountains were up to twice as large as they are today [99]. Researchers have documented broad braidplains downstream of the glacierized headwaters of the Bella Coola and Morice rivers in the central Coast Mountains during the Little Ice Age [100,101]. When glaciers retreated from their Little Ice Age limits, the amount of sediment delivered to the main stems of the Bella Coola, Morice, and other rivers in the Coast Mountains decreased. This, in turn, caused the rivers to alter their planforms from braided to anastomosing. In the case of Morice River, the width of the floodplain decreased by about 50% by the end of the nineteenth century (Figure 10). Since then, floods have perturbed the multi-channel planform of the river several times, but the river has maintained its present overall regime throughout this period [101].

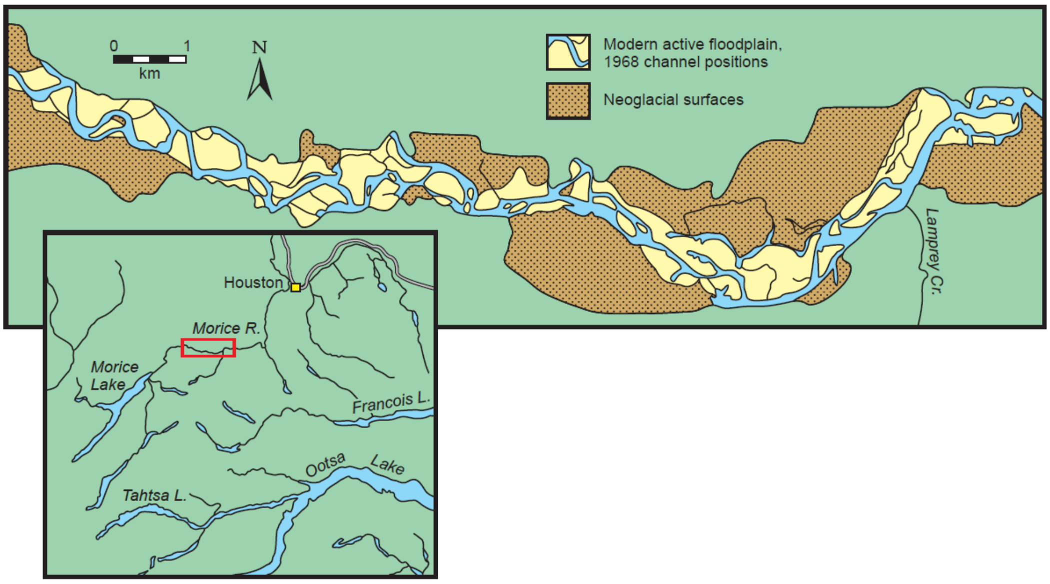

Figure 10. Modern (1990) and Neoglacial floodplains of a section of Morice River, central Coast Mountains, British Columbia. The Neoglacial (19th century) floodplain was twice as wide as the floodplain today. Modified from [101].

Changes such as those in the Bella Coola and Morice river watersheds may not be characteristic of most heavily glacierized catchments in the high mountains of northwest North America. Indeed, changes in the type and temporal scale of runoff from glaciers depend on a large number of factors, including glacier size, elevation range, basin hypsometry, and the proportion of glacier cover in a catchment. Runoff and sediment delivery from larger glaciers may increase for decades during the initial period of negative mass balance, but will inevitably be followed by a decrease in the long term [36,37,102,103]. Recent field-based and modelling studies show that some watersheds with small glaciers have already reached their tipping points and show decreasing annual discharge [104–110]. In contrast, runoff from catchments with the largest ice volumes will likely continue to increase for much or all of the remainder of this century and beyond [2].

4. Impacts of Deglacierization on Ecosystems

We turn now to the impacts of deglacierization on downstream aquatic and riparian plant and animal communities. Seasonal water releases from snow and ice maintain hydrologic base flow, nutrient transport, and ecosystem structure and function [2,111–114]. Vegetation cover and type play an important role in the response of the landscape to hydroclimatic change [115–119]. Vegetation also affects patterns and rates of fluvial channel evolution [120–122]. Increased channel dynamics have consequences for riparian organisms that depend on fluvial bar and bed morphology, grain size, and habitat connectivity [123,124].

A reduction in glacier ice cover leads to changes in the timing and magnitude of runoff peaks [125], with impacts on downstream aquatic ecosystems [36,37,126,127]. Runoff from glacier melt peaks in summer in mid- to high-latitude regions, including northwest North America. This is a time when runoff from other sources is typically lower, thus buffering low dry-season stream discharge and maintaining habitats for fish, amphibians, and other aquatic organisms. Over a multi-decadal timescale, glacierized watersheds in northwest North America will see an initial increase in summer discharge, but this will be followed by reduced runoff during the dry season caused by the decrease in glacier volume [9,103,128,129]. As runoff from glaciers decreases, summer river flows will become more sensitive to smaller precipitation events, resulting in a more stochastic hydrological regime with potential adverse effects on aquatic ecosystems. The replacement of predictable summer glacier melt by less predictable rainfall events and to snowmelt runoff regimes will increase the relative magnitude and seasonal duration of short-term flow variability [37].

In the long term, reduced summer glacier melt will also increase stream temperatures because of (1) an increase in atmospheric energy due to warmer air temperatures, (2) a decline in the contribution of cold water from glacier melt, and (3) the reduced heat capacity of streams with lower flow [130]. At the same time, reductions in bedload and suspended sediment transported by rivers will increase light penetration to the channels, with implications for primary production and photochemical transformation of organic matter [131].

Rising air temperatures and attendant short durations of snow cover influence the length of the growing season and phenology of plant production and consumers and the alpine treeline ecotone [132]. They also impact downstream aquatic ecosystems by governing flow regimes, channel stability, sediment concentration, water temperature, and nutrient supply, and are essential for supporting life during dry periods when snow and ice melt are the main water source. A short-term increase in glacier meltwater runoff will lead to a colder and harsher aquatic environment, and possibly a downstream displacement of aquatic communities [133]. In the long term, however, glacier retreat will result in increases in stream temperatures in meltwater streams. For example, the mean August temperature of an Alaskan stream increased from 2 to 18 °C from 1978 to 2003 due to the complete disappearance of its feeding glacier [134]. Such streams are quickly colonized by aquatic communities adapted to higher water temperatures [135,136].

"Space-for-time" substitutions, a commonly used approach in ecology in which sites covering a gradient in glacier cover are used to predict effects of glacier retreat, show that the richness of local aquatic macrofauna peaks at intermediate levels of glacier runoff [133,137,138]. The reduction and eventual loss of meltwater flow are predicted to: (1) reduce environmental heterogeneity at the watershed level; (2) cause the loss of rare and specialized species from the regional species pool; and (3) elevate algal and herbivore biomasses, thus shifting ecological structure. Reduced meltwater also has been shown to reduce migratory corridors for anadromous fish [36] and to shift life cycles [139].

Change in melting in alpine catchments can affect downstream lakes through changes in water level, turbidity, water chemistry, input of nutrients and other solutes, and the timing of these inputs. These changes will individually and collectively strongly affect benthic and pelagic communities [140,141]. Due to glacier retreat, proglacial lakes are currently forming at a high rate in most arctic and alpine areas of the world [86,142]. Typically, these lakes are initially dominated by microbes and devoid of higher life [143]. Later, they are colonized by algae, protozoans, and invertebrates, and food webs form [144]. As glaciers disappear, or lakes lose connection to them, lake transparency increases, affecting species with high demands for phosphorus and, thus, increasing ultra-violet radiation and visual predation pressure [145–147].

5. Conclusions

Advancing glaciers blocked valleys and, in some cases, re-routed entire river systems when ice sheets formed over the Northern Hemisphere. As we move towards a world with far fewer glaciers and smaller ice sheets, land that has been covered continuously by ice for many tens of thousands of years will become ice-free. As it does so, many rivers in high mountains will be redirected via more hydrologically expedient paths to the sea. In most instances, the redirection will be inconsequential. In other cases, however, the changes might have more significance.

Deglacierization of northwest North America will also induce changes in downstream river planforms and alter aquatic and terrestrial ecosystems. Once glacier-fed streams and rivers pass their meltwater discharge "tipping points", their braided and anastomosing planforms will likely metamorphose into more stable, single-thread systems, with attendant effects on riparian habitats.

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References

1. Bosson, J.; Huss, M.; Osipova, E. Disappearing world heritage glaciers as a keystone of nature conservation in a changing climate. *Earth's Future* **2019**, *7*, 469–479. https://doi.org/10.1029/2018ef001139.
2. Huss, M.; Bookhagen, B.; Huggel, C.; Jacobsen, D.; Bradley, R.; Clague, J.; Vuille, M.; Buytaert, W.; Cayan, D.; Greenwood, G.; et al. Toward mountains without permanent snow and ice. *Earth's Future.* **2017**, *5*, 418–435. https://doi.org/10.1002/2016ef000514.
3. Shugar, D.H.; Clague, J.J. Changing glaciers, changing rivers. In *State of the Mountains Report 1*; Parrott, L., Robinson, Z, Hik, D., Eds.; Alpine Club of Canada: Calgary, AB, Canada, 2018; pp. 4–11, ISBN 9780920330715.
4. Vaughan, D.G.; Comiso, J.C.; Allison, I.; Carrasco, J.; Kaser, G.; Kwok, R.; Mote, P.W.; Murray, T.; Paul, F.; Ren, J.; et al. Observations: Cryosphere. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., Eds.; Cambridge University Press: Cambridge, UK, New York, NY, USA, 2014; pp. 317–382, ISBN 9781107415324.
5. Berthier, E.; Schiefer, E.; Clarke, G.K.C.; Menounos, B.; Remy, F. Contribution of Alaskan glaciers to sea-level rise derived from satellite imagery. *Nat. Geosci.* **2010**, *3*, 92–95. https://doi.org/10.1038/ngeo737.
6. Evans, S.G.; Clague, J.J. Recent climatic change and catastrophic geomorphic processes in mountain environments. *Geomorphology* **1994**, *10*, 107–128. https://doi.org/10.1016/b978-0-444-82012-9.50012-8.
7. Larsen, C.F.; Motyka, R.J.; Arendt, A.A.; Echelmeyer, K.A.; Geissler, P.E. Glacier changes in southeast Alaska and northwest British Columbia and contribution to sea level rise. *J. Geophys. Res.* **2007**, *112*, F01007. https://doi.org/10.1029/2006jf000586.
8. Dyke, A.S.; Prest, V.K. *Late Wisconsinan and Holocene Retreat of the Laurentide Ice Sheet*; Geological Survey of Canada: Ottawa, ON, Canada, 1987; Map 1702A; p. 1.
9. Clarke, G.K.C.; Jarosch, A.H.; Anslow, F.S.; Radić, V.; Menounos, B. Projected deglaciation of western Canada in the twenty-first century. *Nat. Geosci.* **2015**, *8*, 372–377. https://doi.org/10.1038/ngeo2407.
10. Hugonnet, R.; McNabb, R.; Berthier, E.; Menounos, B.; Nuth, C.; Girod, L.; Farinotti, D.; Huss, M.; Dussaillant, I.; Brun, F.; et al. Accelerated global glacier mass loss in the early twenty-first century. *Nature* **2021**, *592*, 726–731. https://doi.org/10.1038/s41586-021-03436-z.
11. Shannon, S.; Smith, R.; Wiltshire, A.; Payne, T.; Huss, M.; Betts, R.; Caesar, J.; Koutroulis, A.; Jones, D.; Harrison, S. Global glacier volume projections under high-end climate change scenarios. *Cryosphere* **2019**, *13*, 325–350. https://doi.org/10.5194/tc-13-325-2019.
12. Harrison, S. Climate sensitivity: Implications for the response of geomorphological systems to future climate change. In *Periglacial and Paraglacial Processes and Environments*; Knight, J., Harrison, S., Eds.; Geological Society: London, UK, 2009; Special Publication 320; pp. 257–265, ISBN 9781862392816.
13. Lane, S.N.; Bakker, M.; Gabbud, C.; Micheletti, N.; Saugy, J.-N. Sediment export, transient landscape response and catchment-scale connectivity following rapid climate warming and Alpine glacier recession. *Geomorphology* **2017**, *277*, 210–227. https://doi.org/10.1016/j.geomorph.2016.02.015.
14. Micheletti, N.; Chandler, J.H.; Lane, S.N. Investigating the geomorphological potential of freely available and accessible structure-from-motion photogrammetry using a smartphone. *Earth Surf. Process. Landforms* **2015**, *40*, 473–486. https://doi.org/10.1002/esp.3648.
15. Zhao, D.; Wu, S. Projected Changes in permafrost active layer thickness over the Qinghai-Tibet Plateau under climate change. *Water Resour. Res.* **2019**, *55*, 7860–7875. https://doi.org/10.1029/2019wr024969.
16. Coe, J.A.; Bessette-Kirton, E.K.; Geertsema, M. Increasing rock-avalanche size and mobility in Glacier Bay National Park and Preserve, Alaska detected from 1984 to 2016 Landsat imagery. *Landslides* **2018**, *15*, 393–407. https://doi.org/10.1007/s10346-017-0879-7.
17. Draebing, D.; Krautblatter, M. The efficacy of frost weathering processes in alpine rockwalls. *Geophys. Res. Lett.* **2019**, *46*, 6516–6524. https://doi.org/10.1029/2019gl081981.

18. Drewes, J.; Moreiras, S.; Korup, O. Permafrost activity and atmospheric warming in the Argentinian Andes. *Geomorphology* **2018**, *323*, 13–24. https://doi.org/10.1016/j.geomorph.2018.09.005.
19. Gądek, B.; Grabiec, M.; Kędzia, S.; Rączkowska, Z. Reflection of climate changes in the structure and morphodynamics of talus slopes (the Tatra Mountains, Poland). *Geomorphology* **2016**, *263*, 39–49. https://doi.org/10.1016/j.geomorph.2016.03.024.
20. Geertsema, M.; Clague, J.J.; Schwab, J.W.; Evans, S.G. An overview of recent large catastrophic landslides in northern British Columbia, Canada. *Eng. Geol.* **2006**, *83*, 120–143. https://doi.org/10.1016/j.enggeo.2005.06.028.
21. Gruber, S.; Hoelzle, M.; Haeberli, W. Permafrost thaw and destabilization of Alpine rock walls in the hot summer of 2003. *Geophys. Res. Lett.* **2004**, *31*, L13504. https://doi.org/10.1029/2004gl020051.
22. Gruber, S.; Haeberli, W. Permafrost in steep bedrock slopes and its temperature-related destabilization following climate change. *J. Geophys. Res. Earth Surf.* **2007**, *112*, 10 pp. https://doi.org/10.1029/2006jf000547.
23. Haeberli, W.; Schaub, Y.; Huggel, C. Increasing risks related to landslides from degrading permafrost into new lakes in deglaciating mountain ranges. *Geomorphology* **2017**, *293*, 405–417. https://doi.org/10.1016/j.geomorph.2016.02.009.
24. Knight, J.; Harrison, S. Mountain glacial and paraglacial environments under global climate change: Lessons from the past, future directions and policy implications. *Geogr. Ann. Ser. A Phys. Geogr.* **2014**, *96*, 245–264. https://doi.org/10.1111/geoa.12051.
25. Marshall, J.A.; Roering, J.J.; Gavin, D.G.; Granger, D.E. Late Quaternary climatic controls on erosion rates and geomorphic processes in western Oregon, USA. *GSA Bull.* **2017**, *129*, 715–731. https://doi.org/10.1130/b31509.1.
26. Patton, A.I.; Rathburn, S.L.; Capps, D.M. Landslide response to climate change in permafrost regions. *Geomorphology* **2019**, *340*, 116–128. https://doi.org/10.1016/j.geomorph.2019.04.029.
27. Stoffel, M.; Huggel, C. Effects of climate change on mass movements in mountain environments. *Prog. Phys. Geogr. Earth Environ.* **2012**, *36*, 421–439. https://doi.org/10.1177/0309133312441010.
28. Clague, J.J.; O'Connor, J.E. Glacier-related outburst floods. In *Snow and Ice-Related Hazards, Risks, and Disasters*; Haeberli, W., Whiteman, C., Eds.; Elsevier: Amsterdam, The Netherlands, 2021; pp. 467–499, ISBN 9780128171295.
29. O'Connor, J.E.; Clague, J.J.; Walder, J.S.; Manville, V.; Beebee, R.A. 6.36 – Outburst floods. In *Treatise on Geomorphology*, 2nd ed.; Shroder, J.F., Ed.; Academic: Oxford, UK, 2022, ISBN 9780128182345.
30. Duethmann, D.; Bolch, T.; Farinotti, D.; Kriegel, D.; Vorogushyn, S.; Merz, B.; Pieczonka, T.; Jiang, T.; Su, B.; Güntner, A. Attribution of streamflow trends in snow and glacier melt-dominated catchments of the Tarim River, Central Asia. *Water Resour. Res.* **2015**, *51*, 4727–4750. https://doi.org/10.1002/2014wr016716.
31. East, A.E.; Sankey, J.B. Geomorphic and sedimentary effects of modern climate change: Current and anticipated future conditions in the western United States. *Rev. Geophys.* **2020**, *58*, e2019RG000692. https://doi.org/10.1029/2019rg000692.
32. Farinotti, D.; Longuevergne, L.; Moholdt, G.; Duethmann, D.; Mölg, T.; Bolch, T.; Vorogushyn, S.; Güntner, A. Substantial glacier mass loss in the Tien Shan over the past 50 years. *Nat. Geosci.* **2015**, *8*, 716–722. https://doi.org/10.1038/ngeo2513.
33. Leach, J.A.; Moore, R.D. Empirical stream thermal sensitivities may underestimate stream temperature response to climate warming. *Water Resour. Res.* **2019**, *55*, 5453–5467. https://doi.org/10.1029/2018wr024236.
34. Mantua, N.; Tohver, I.; Hamlet, A. Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. *Clim. Change* **2010**, *102*, 187–223. https://doi.org/10.1007/s10584-010-9845-2.
35. Mantua, N.J.; Crozier, L.G.; Reed, T.E.; Schindler, D.E.; Waples, R.S. Response of chinook salmon to climate change. *Nat. Clim. Change* **2015**, *5*, 613–615. https://doi.org/10.1038/nclimate2670.
36. Milner, A.M.; Brown, L.E.; Hannah, D.M. Hydroecological response of river systems to shrinking glaciers. *Hydrol. Process.* **2009**, *23*, 62–77. https://doi.org/10.1002/hyp.7197.
37. Milner, A.M.; Khamis, K.; Battin, T.J.; Brittain, J.E.; Barrand, N.; Füreder, L.; Cauvy-Fraunié, S.; Gislason, G.M.; Jacobsen, D.; Hannah, D.; et al. Glacier shrinkage driving global changes in downstream systems. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 9770–9778. https://doi.org/10.1073/pnas.1619807114.
38. Muñoz, N.J.; Farrell, A.P.; Heath, J.W.; Neff, B.D. Adaptive potential of a Pacific salmon challenged by climate change. *Nat. Clim. Change* **2015**, *5*, 163–166. https://doi.org/10.1038/nclimate2473.
39. Vuille, M.; Carey, M.; Huggel, C.; Buytaert, W.; Rabatel, A.; Jacobsen, D.; Soruco, A.; Villacis, M.; Yarleque, C.; Timm, O.E.; et al. Rapid decline of snow and ice in the tropical Andes—Impacts, uncertainties and challenges ahead. *Earth-Sci. Rev.* **2018**, *176*, 195–213. https://doi.org/10.1016/j.earscirev.2017.09.019.
40. Wade, A.A.; Beechie, T.J.; Fleishman, E.; Mantua, N.J.; Wu, H.; Kimball, J.S.; Stoms, D.M.; Stanford, J.A. Steelhead vulnerability to climate change in the Pacific Northwest. *J. Appl. Ecol.* **2013**, *50*, 1093–1104. https://doi.org/10.1111/1365-2664.12137.
41. Pitman, K.J.; Moore, J.W.; Huss, M.; Sloat, M.R.; Whited, D.C.; Beechie, T.J.; Brenner, R.; Hood, E.W.; Milner, A.M.; Pess, G.R.; et al. Glacier retreat creating new Pacific salmon habitat in western North America. *Nat. Commun.* **2021**, *12*, 6816. https://doi.org/10.1038/s41467-021-26897-2.
42. Pitman, K.J.; Moore, J.W.; Sloat, M.R.; Beaudreau, A.H.; Bidlack, A.L.; Brenner, R.E.; Hood, E.W.; Pess, G.R.; Mantua, N.J.; Milner, A.M.; et al. Glacier retreat and Pacific salmon. *Bioscience* **2020**, *70*, 220–236. https://doi.org/10.1093/biosci/biaa015.
43. Duk-Rodkin, A.; Barendregt, R.; White, J.; Singhroy, V. Geologic evolution of the Yukon River: Implications for placer gold. *Quat. Int.* **2001**, *82*, 5–31. https://doi.org/10.1016/s1040-6182(01)00006-4.
44. Ryan, J.J.; Hayward, N.; Jackson, L.E. Landscape antiquity and Cenozoic drainage development of southern Yukon, through restoration modeling of the Tintina Fault. *Can. J. Earth Sci.* **2017**, *54*, 1085–1100. https://doi.org/10.1139/cjes-2017-0053.

45. Tempelman-Kluit, D. Evolution of physiography and drainage in southern Yukon. *Can. J. Earth Sci.* **1980**, *17*, 1189–1203. https://doi.org/10.1139/e80-125.
46. Andrews, G.D.; Russell, J.K.; Brown, S.R.; Enkin, R.J. Pleistocene reversal of the Fraser River, British Columbia. *Geology* **2012**, *40*, 111–114. https://doi.org/10.1130/g32488.1.
47. RGI Consortium. *Randolph Glacier Inventory—A Dataset of Global Glacier Outlines: Version 5.0 [Data Set]*; National Snow and Ice Data Center: Boulder, CO, USA., 2015. https://doi.org/10.7265/gq4p-zz56.
48. Shugar, D.H.; Clague, J.J.; Best, J.L.; Schoof, C.; Willis, M.J.; Copland, L.; Roe, G.H. River piracy and drainage basin reorganization led by climate-driven glacier retreat. *Nat. Geosci.* **2017**, *10*, 370–375. https://doi.org/10.1038/ngeo2932.
49. Zabel, N.A.; Hall, R.I.; Branfireun, B.A.; Swanson, H.K. Mercury accumulation in sediments of Lhù'ààn Mân' (Kluane Lake, YT): Response to past hydrological change. *Arctic, Antarct. Alp. Res.* **2021**, *53*, 179–195. https://doi.org/10.1080/15230430.2021.1940790.
50. Bachelder, J.; Cadieux, M.; Liu-Kang, C.; Lambert, P.; Filoche, A.; Galhardi, J.A.; Hadioui, M.; Chaput, A.; Bastien-Thibault, M.-P.; Wilkinson, K.J.; et al. Chemical and microphysical properties of wind-blown dust near an actively retreating glacier in Yukon, Canada. *Aerosol Sci. Technol.* **2020**, *54*, 2–20. https://doi.org/10.1080/02786826.2019.1676394.
51. McKnight, E. Characterizing and monitoring the water properties and dynamics of Lhù'ààn Mā̃n (Kluane Lake), Yukon, in the face of climate change. *Arctic* **2017**, *70*, 435–440. https://doi.org/10.14430/arctic4692.
52. McKnight, E.A.; Swanson, H.; Brahney, J.; Hik, D.S. The physical and chemical limnology of Yukon's largest lake, Lhù'ààn Mân' (Kluane Lake), prior to the 2016 'A'ą¨y Chù' diversion. *Arct. Sci.* **2021**, *7*, 655–678. https://doi.org/10.1139/as-2020-0012.
53. Clague, J.J.; Evans, S.G. Historic retreat of Grand Pacific and Melbern glaciers Saint Elias Mountains, Canada: An analogue for decay of the Cordilleran ice sheet at the end of the Pleistocene?. *J. Glaciol.* **1993**, *39*, 619–624. https://doi.org/10.3189/s0022143000016518.
54. Farinotti, D.; Huss, M.; Fürst, J.J.; Landmann, J.; Machguth, H.; Maussion, F.; Pandit, A. A consensus estimate for the ice thickness distribution of all glaciers on Earth. *Nat. Geosci.* **2019**, *12*, 168–173. https://doi.org/10.1038/s41561-019-0300-3.
55. Loso, M.G.; Larsen, C.F.; Tober, B.S.; Christoffersen, M.; Fahnestock, M.; Holt, J.W.; Truffer, M. Quo vadis, Alsek? Climate-driven glacier retreat may change the course of a major river outlet in southern Alaska. *Geomorphology* **2021**, *384*, 107701. https://doi.org/10.1016/j.geomorph.2021.107701.
56. Pelto, M. Grand Plateau Glacier retreat, Alaska. AGU Advancing Earth and Space Science Blogosphere. Available online: http://blogs.agu.org/fromaglaciersperspective/2011/02/04/grand-plateau-glacier-retreat/ (accessed on 7 December 2022).
57. Pelto, M. North Fork Grand Plateau Glacier, Alaska—Spectacular 3 km Retreat 2013-15. AGU Advancing Earth and Space Science Blogosphere. Available online: http://blogs.agu.org/fromaglaciersperspective/2016/05/01/south-fork-alsek-glacier-alaska-spectacular-3-km-retreat-2013-15/ (accessed on 7 December 2022).
58. Haritashya, U.K.; Kargel, J.S.; Shugar, D.H.; Leonard, G.J.; Strattman, K.; Watson, C.S.; Shean, D.; Harrison, S.; Mandli, K.T.; Regmi, D. Evolution and controls of large glacial lakes in the Nepal Himalaya. *Remote. Sens.* **2018**, *10*, 798. https://doi.org/10.3390/rs10050798.
59. Anderson, S.; Radić, V. Identification of local water resource vulnerability to rapid deglaciation in Alberta. *Nat. Clim. Change.* **2020**, *10*, 933–938. https://doi.org/10.1038/s41558-020-0863-4.
60. Birsan, M.-V.; Molnar, P.; Burlando, P.; Pfaundler, M. Streamflow trends in Switzerland. *J. Hydrol.* **2005**, *314*, 312–329. https://doi.org/10.1016/j.jhydrol.2005.06.008.
61. Chesnokova, A.; Baraër, M.; Laperrière-Robillard, T.; Huh, K. Linking mountain glacier retreat and hydrological changes in southwestern Yukon. *Water Resour. Res.* **2020**, *56*, e2019WR025706. https://doi.org/10.1029/2019wr025706.
62. Frans, C.; Istanbulluoglu, E.; Lettenmaier, D.P.; Fountain, A.G.; Riedel, J. Glacier Recession and the Response of Summer Streamflow in the Pacific Northwest United States, 1960–2099. *Water Resour. Res.* **2018**, *54*, 6202–6225. https://doi.org/10.1029/2017wr021764.
63. Kormos, P.R.; Luce, C.H.; Wenger, S.J.; Berghuijs, W.R. Trends and sensitivities of low streamflow extremes to discharge timing and magnitude in Pacific Northwest mountain streams. *Water Resour. Res.* **2016**, *52*, 4990–5007. https://doi.org/10.1002/2015wr018125.
64. Lane, S.N.; Nienow, P.W. Decadal scale climate forcing of alpine glacial hydrological systems. *Water Resour. Res.* **2019**, *55*, 2478–2492. https://doi.org/10.1029/2018wr024206.
65. Micheletti, N.; Lane, S.N. Water yield and sediment export in small, partially glaciated Alpine watersheds in a warming climate. *Water Resour. Res.* **2016**, *52*, 4924–4943. https://doi.org/10.1002/2016wr018774.
66. Stewart, I.T. Changes in snowpack and snowmelt runoff for key mountain regions. *Hydrol. Process.* **2009**, *23*, 78–94. https://doi.org/10.1002/hyp.7128.
67. Stewart, I.T.; Cayan, D.R.; Dettinger, M.D. Changes toward earlier streamflow timing across western North America. *J. Clim.* **2005**, *18*, 1136–1155. https://doi.org/10.1175/jcli3321.1.
68. Stumbaugh, M.; Hamlet, A.F. Effects of climate change on extreme low-flows in small lowland tributaries in the Skagit River basin. *Northwest Sci.* **2016**, *90*, 44–56. https://doi.org/10.3955/046.090.0105.
69. Beamer, J.P.; Hill, D.F.; McGrath, D.; Arendt, A.; Kienholz, C. Hydrologic impacts of changes in climate and glacier extent in the Gulf of Alaska watershed. *Water Resour. Res.* **2017**, *53*, 7502–7520. https://doi.org/10.1002/2016wr020033.
70. Hallet, B.; Hunter, L.; Bogen, J. Rates of erosion and sediment evacuation by glaciers: A review of field data and their implications. *Glob. Planet. Change*, **1996**, *12*, 213–235. https://doi.org/10.1016/0921-8181(95)00021-6.

71. Koppes, M.N.; Montgomery, D.R. The relative efficacy of fluvial and glacial erosion over modern to orogenic timescales. *Nat. Geosci.* **2009**, *2*, 644–647. https://doi.org/10.1038/ngeo616.
72. Lawson, D.E. *Glaciologic and Glaciohydraulic Effects on Runoff and Sediment Yield in Glacierized Basins*; U.S. Army Corp of Engineers, Cold Regions Research Laboratory: Hanover, NH, USA, 1993; Technical Report AD-A275 134.
73. Fischer, L.; Huggel, C.; Kääb, A.; Haeberli, W. Slope failures and erosion rates on a glacierized high-mountain face under climatic changes. *Earth Surf. Process. Landforms* **2013**, *38*, 836–846. https://doi.org/10.1002/esp.3355.
74. Geertsema, M.; Menounos, B.; Bullard, G.; Carrivick, J.L.; Clague, J.J.; Dai, C.; Donati, D.; Ekstrom, G.; Jackson, J.M.; Lynett, P.; et al. The 28 November 2020 landslide, tsunami, and outburst flood—A hazard cascade associated with rapid deglaciation at Elliot Creek, British Columbia, Canada. *Geophys. Res. Lett.* **2022**, *49*, e2021GL096716. https://doi.org/10.1029/2021gl096716.
75. Huggel, C.; Clague, J.J.; Korup, O. Is climate change responsible for changing landslide activity in high mountains? *Earth Surf. Process. Landforms* **2012**, *37*, 77–91. https://doi.org/10.1002/esp.2223.
76. Shugar, D.H.; Jacquemart, M.; Shean, D.; Bhushan, S.; Upadhyay, K.; Sattar, A.; Schwanghart, W.; McBride, S.; de Vries, M.V.W.; Mergili, M.; et al. A massive rock and ice avalanche caused the 2021 disaster at Chamoli, Indian Himalaya. *Science* **2021**, *373*, 300–306. https://doi.org/10.1126/science.abh4455.
77. Tunnicliffe, J.; Church, M.; Enkin, R.J. Postglacial sediment yield to Chilliwack Lake, British Columbia, Canada. *Boreas* **2012**, *41*, 84–101. https://doi.org/10.1111/j.1502-3885.2011.00219.x.
78. Wohl, E.; Brierley, G.; Cadol, D.; Coulthard, T.J.; Covino, T.; Fryirs, K.A.; Grant, G.; Hilton, R.G.; Lane, S.N.; Magilligan, F.J.; et al. Connectivity as an emergent property of geomorphic systems. *Earth Surf. Process. Landforms* **2019**, *44*, 4–26. https://doi.org/10.1002/esp.4434.
79. Ballantyne, C.K. Paraglacial geomorphology. *Quat. Sci. Rev.* **2002**, *21*, 1935–2017. https://doi.org/10.1016/s0277-3791(02)00005-7.
80. Tranmer, A.W.; Goodwin, P.; Caamaño, D. Assessment of alluvial trends toward dynamic equilibrium under chronic climatic forcing. *Adv. Water Resour.* **2018**, *120*, 19–34. https://doi.org/10.1016/j.advwatres.2017.11.015.
81. Li, D.; Lu, X.; Overeem, I.; Walling, D.E.; Syvitski, J.; Kettner, A.J.; Bookhagen, B.; Zhou, Y.; Zhang, T. Exceptional increases in fluvial sediment fluxes in a warmer and wetter High Mountain Asia. *Science* **2021**, *374*, 599–603. https://doi.org/10.1126/science.abi9649.
82. Korup, O.; Tweed, F. Ice, moraine, and landslide dams in mountainous terrain. *Quat. Sci. Rev.* **2007**, *26*, 3406–3422. https://doi.org/10.1016/j.quascirev.2007.10.012.
83. Richardson, S.D.; Reynolds, J.M. Degradation of ice-cored moraine dams; implications for hazard development. In *Debris-Covered Glaciers*; Nakawo, M., Raymond, C.F., Fountain, A., Eds.; IAHS-AISH: Seattle, WA, USA, 2000; Publication 264; pp. 187–197, ISBN 1901502317.
84. Stoffel, M.; Tiranti, D.; Huggel, C. Climate change impacts on mass movements—Case studies from the European Alps. *Sci. Total Environ.* **2014**, *493*, 1255–1266. https://doi.org/10.1016/j.scitotenv.2014.02.102.
85. Harrison, S.; Kargel, J.S.; Huggel, C.; Reynolds, J.; Shugar, D.H.; Betts, R.A.; Emmer, A.; Glasser, N.; Haritashya, U.K.; Klimeš, J.; et al. Climate change and the global pattern of moraine-dammed glacial lake outburst floods. *Cryosphere* **2018**, *12*, 1195–1209. https://doi.org/10.5194/tc-12-1195-2018.
86. Shugar, D.H.; Burr, A.; Haritashya, U.K.; Kargel, J.S.; Watson, C.S.; Kennedy, M.C.; Bevington, A.R.; Betts, R.A.; Harrison, S.; Strattman, K. Rapid worldwide growth of glacial lakes since 1990. *Nat. Clim. Change* **2020**, *10*, 1–7. https://doi.org/10.1038/s41558-020-0855-4.
87. Dussaillant, A.; Benito, G.; Buytaert, W.; Carling, P.; Meier, C.; Espinoza, F. Repeated glacial-lake outburst floods in Patagonia: An increasing hazard? *Nat. Hazards* **2010**, *54*, 469–481. https://doi.org/10.1007/s11069-009-9479-8.
88. Church, M.; Ryder, J.M. Paraglacial sedimentation: A consideration of fluvial processes conditioned by glaciation. *GSA Bull.* **1972**, *83*, 3059–3072. https://doi.org/10.1130/0016-7606(1972)83[3059:psacof]2.0.co;2.
89. Dadson, S.J.; Church, M. Postglacial topographic evolution of glaciated valleys: A stochastic landscape evolution model. *Earth Surf. Process. Landforms* **2005**, *30*, 1387–1403. https://doi.org/10.1002/esp.1199.
90. Friele, P.A.; Clague, J.J. Paraglacial geomorphology of Quaternary volcanic landscapes in the southern Coast Mountains, British Columbia. In *Periglacial and Paraglacial Processes and Environments*; Knight, J., Harrison, S., Eds.; Geological Society: London, UK, 2009; Special Publication 320; pp. 219–233, ISBN 9781862392816.
91. Koppes, M.; Sylwester, R.; Rivera, A.; Hallet, B. Variations in sediment yield over the advance and retreat of a calving glacier, Laguna San Rafael, North Patagonian Icefield. *Quat. Res.* **2010**, *73*, 84–95. https://doi.org/10.1016/j.yqres.2009.07.006.
92. Stott, T.; Mount, N. Alpine proglacial suspended sediment dynamics in warm and cool ablation seasons: Implications for global warming. *J. Hydrol.* **2007**, *332*, 259–270. https://doi.org/10.1016/j.jhydrol.2006.07.001.
93. Larsen, D.J.; Miller, G.H.; Geirsdóttir, .; Thordarson, T. A 3000-year varved record of glacier activity and climate change from the proglacial lake Hvítárvatn, Iceland. *Quat. Sci. Rev.* **2011**, *30*, 2715–2731. https://doi.org/10.1016/j.quascirev.2011.05.026.
94. Menounos, B.; Clague, J.J. Reconstructing hydro-climatic events and glacier fluctuations over the past millennium from annually laminated sediments of Cheakamus Lake, southern Coast Mountains, British Columbia, Canada. *Quat. Sci. Rev.* **2008**, *27*, 701–713. https://doi.org/10.1016/j.quascirev.2008.01.007.
95. Schiefer, E.; Hassan, M.A.; Menounos, B.; Pelpola, C.P.; Slaymaker, O. Interdecadal patterns of total sediment yield from a montane catchment, southern Coast Mountains, British Columbia, Canada. *Geomorphology* **2010**, *118*, 207–212. https://doi.org/10.1016/j.geomorph.2010.01.001.

96. Chew, L.; Ashmore, P. Channel adjustment and a test of rational regime theory in a proglacial braided stream. *Geomorphology* **2001**, *37*, 43–63. https://doi.org/10.1016/s0169-555x(00)00062-3.
97. Kershaw, J.A.; Clague, J.J.; Evans, S.G. Geomorphic and sedimentological signature of a two-phase outburst flood from moraine-dammed Queen Bess Lake, British Columbia, Canada. *Earth Surf. Process. Landforms* **2005**, *30*, 1–25. https://doi.org/10.1002/esp.1122.
98. Menounos, B.; Osborn, G.; Clague, J.J.; Luckman, B.H. Latest Pleistocene and Holocene glacier fluctuations in western Canada. *Quat. Sci. Rev.* **2009**, *28*, 2049–2074. https://doi.org/10.1016/j.quascirev.2008.10.018.
99. Koch, J.; Clague, J.J.; Osborn, G.D. Glacier fluctuations during the past millennium in Garibaldi Provincial Park, southern Coast Mountains, British Columbia. *Can. J. Earth Sci.* **2007**, *44*, 1215–1233. https://doi.org/10.1139/e07-019.
100. Church, M. Pattern of Instability in a wandering gravel bed channel. In *Modern and Ancient Fluvial Systems*; Collinson, J.D., Lewin, J., Eds.; Blackwell Publishing Ltd.: Oxford, UK, 1983; pp. 169–180, ISBN 9780632009978.
101. Gottesfeld, A.S.; Gottesfeld, L.M.J. Floodplain dynamics of a wandering river, dendrochronology of the Morice River, British Columbia, Canada. *Geomorphology* **1990**, *3*, 159–179. https://doi.org/10.1016/0169-555x(90)90043-p.
102. Mark, B.G.; Baraer, M.; Fernandez, A.; Immerzeel, W.; Moore, R.D.; Weingartner, R. Glaciers as water resources. In *The High-Mountain Cryosphere: Environmental Changes and Human Risks*; Kääb, A., Huggel, C., Clague, J.J., Carey, M., Eds.; Cambridge University Press: Cambridge, UK, 2015; pp. 184–203, ISBN 978-1107662759.
103. Moore, R.D.; Fleming, S.W.; Menounos, B.; Wheate, R.; Fountain, A.; Stahl, K.; Holm, K.; Jakob, M. Glacier change in western North America: Influences on hydrology, geomorphic hazards and water quality. *Hydrol. Process.* **2009**, *23*, 42–61. https://doi.org/10.1002/hyp.7162.
104. Baraer, M.; Mark, B.G.; McKenzie, J.M.; Condom, T.; Bury, J.; Huh, K.-I.; Portocarrero, C.; Gómez, J.; Rathay, S. Glacier recession and water resources in Peru's Cordillera Blanca. *J. Glaciol.* **2012**, *58*, 134–150. https://doi.org/10.3189/2012jog11j186.
105. Bliss, A.; Hock, R.; Radić, V. Global response of glacier runoff to twenty-first century climate change. *J. Geophys. Res. Earth Surf.* **2014**, *119*, 717–730. https://doi.org/10.1002/2013jf002931.
106. Farinotti, D.; Usselmann, S.; Huss, M.; Bauder, A.; Funk, M. Runoff evolution in the Swiss Alps: Projections for selected high-alpine catchments based on ENSEMBLES scenarios. *Hydrol. Process.* **2012**, *26*, 1909–1924. https://doi.org/10.1002/hyp.8276.
107. Frans, C.; Istanbulluoglu, E.; Lettenmaier, D.P.; Clarke, G.; Bohn, T.J.; Stumbaugh, M. Implications of decadal to century scale glacio-hydrological change for water resources of the Hood River basin, OR, USA. *Hydrol. Process.* **2016**, *30*, 4314–4329. https://doi.org/10.1002/hyp.10872.
108. Immerzeel, W.W.; Pellicciotti, F.; Bierkens, M.F.P. Rising river flows throughout the twenty-first century in two Himalayan glacierized watersheds. *Nat. Geosci.* **2013**, *6*, 742–745. https://doi.org/10.1038/ngeo1896.
109. Lutz, A.; Immerzeel, W.; Shrestha, A.B.; Bierkens, M.F. Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. *Nat. Clim. Change.* **2014**, *4*, 587–592. https://doi.org/10.1038/nclimate2237.
110. Ragettli, S.; Immerzeel, W.W.; Pellicciotti, F. Contrasting climate change impact on river flows from high-altitude catchments in the Himalayan and Andes Mountains. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 9222–9227. https://doi.org/10.1073/pnas.1606526113.
111. Biemans, H.; Siderius, C.; Lutz, A.F.; Nepal, S.; Ahmad, B.; Hassan, T.; Von Bloh, W.; Wijngaard, R.R.; Wester, P.; Shrestha, A.B.; et al. Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain. *Nat. Sustain.* **2019**, *2*, 594–601. https://doi.org/10.1038/s41893-019-0305-3.
112. Immerzeel, W.W.; Van Beek, L.P.H.; Bierkens, M.F.P. Climate change will affect the Asian Water Towers. *Science* **2010**, *328*, 1382–1385.
113. Viviroli, D.; Archer, D.R.; Buytaert, W.; Fowler, H.J.; Greenwood, G.B.; Hamlet, A.F.; Huang, Y.; Koboltschnig, G.; Litaor, M.I.; López-Moreno, J.I.; et al. Climate change and mountain water resources: Overview and recommendations for research, management and policy. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 471–504. https://doi.org/10.5194/hess-15-471-2011.
114. Xu, J.; Grumbine, R.E.; Shrestha, A.; Eriksson, M.; Yang, X.; Wang, Y.; Wilkes, A. The melting Himalayas: Cascading effects of climate change on water, biodiversity, and livelihoods. *Conserv. Biol.* **2009**, *23*, 520–530. https://doi.org/10.1111/j.1523-1739.2009.01237.x.
115. Barreiro-Lostres, F.; Moreno, A.; González-Sampériz, P.; Giralt, S.; Nadal-Romero, E.; Valero-Garcés, B. Erosion in Mediterranean mountain landscapes during the last millennium: A quantitative approach based on lake sediment sequences (Iberian Range, Spain). *Catena* **2017**, *149*, 782–798. https://doi.org/10.1016/j.catena.2016.05.024.
116. Pelletier, J.D.; Murray, A.B.; Pierce, J.L.; Bierman, P.R.; Breshears, D.D.; Crosby, B.T.; Ellis, M.; Foufoula-Georgiou, E.; Heimsath, A.M.; Houser, C.; et al. Forecasting the response of Earth's surface to future climatic and land use changes: A review of methods and research needs. *Earth's Future.* **2015**, *3*, 220–251. https://doi.org/10.1002/2014ef000290.
117. Reinhardt, L.; Jerolmack, D.; Cardinale, B.J.; Vanacker, V.; Wright, J. Dynamic interactions of life and its landscape: Feedbacks at the interface of geomorphology and ecology. *Earth Surf. Process. Landforms* **2010**, *35*, 78–101. https://doi.org/10.1002/esp.1912.
118. Werner, C.; Schmid, M.; Ehlers, T.A.; Fuentes-Espoz, J.P.; Steinkamp, J.; Forrest, M.; Liakka, J.; Maldonado, A.; Hickler, T. Effect of changing vegetation and precipitation on denudation—Part 1: Predicted vegetation composition and cover over the last 21 thousand years along the Coastal Cordillera of Chile. *Earth Surf. Dyn.* **2018**, *6*, 829–858. https://doi.org/10.5194/esurf-6-829-2018.
119. Yetemen, O.; Saco, P.M.; Istanbulluoglu, E. Ecohydrology controls the geomorphic response to climate change. *Geophys. Res. Lett.* **2019**, *46*, 8852–8861. https://doi.org/10.1029/2019gl083874.

120. Corenblit, D.; Davies, N.S.; Steiger, J.; Gibling, M.R.; Bornette, G. Considering river structure and stability in the light of evolution: Feedbacks between riparian vegetation and hydrogeomorphology. *Earth Surf. Process. Landforms* **2015**, *40*, 189–207. https://doi.org/10.1002/esp.3643.
121. Gurnell, A. Plants as river system engineers. *Earth Surf. Process. Landfoms* **2014**, *39*, 4–25. https://doi.org/10.1002/esp.3397.
122. Ielpi, A.; Lapôtre, M.G.A. A tenfold slowdown in river meander migration driven by plant life. *Nat. Geosci.* **2020**, *13*, 82–86. https://doi.org/10.1038/s41561-019-0491-7.
123. Beeson, H.W.; Flitcroft, R.L.; Fonstad, M.A.; Roering, J.J. Deep-seated landslides drive variability in valley width and increase connectivity of salmon habitat in the Oregon Coast Range. *JAWRA J. Am. Water Resour. Assoc.* **2018**, *54*, 1325–1340. https://doi.org/10.1111/1752-1688.12693.
124. Death, R.G.; Fuller, I.; Macklin, M.G. Resetting the river template: The potential for climate-related extreme floods to transform river geomorphology and ecology. *Freshw. Biol.* **2015**, *60*, 2477–2496. https://doi.org/10.1111/fwb.12639.
125. Jansson, P.; Hock, R.; Schneider, T. The concept of glacier storage: A review. *J. Hydrol.* **2003**, *282*, 116–129. https://doi.org/10.1016/s0022-1694(03)00258-0.
126. Milner, A.M. Glacial recession and freshwater ecosystems in coastal Alaska. In *Freshwaters of Alaska, Ecological Syntheses*; Milner, A.M., Oswood, M.W., Eds.; Springer: New York, NY, USA, 1997; Ecological Studies 119; pp. 303–330, ISBN 9781461206774.
127. Milner, A.M.; Robertson, A.; Brown, L.; Sønderland, S.H.; McDermott, M.; Veal, A.J. Evolution of a stream ecosystem in recently deglaciated terrain. *Ecology* **2011**, *92*, 1924–1935. https://doi.org/10.1890/10-2007.1.
128. O'Neel, S.; Hood, E.; Arendt, A.; Sass, L. Assessing streamflow sensitivity to variations in glacier mass balance. *Clim. Change.* **2014**, *123*, 329–341. https://doi.org/10.1007/s10584-013-1042-7.
129. Stahl, K.; Moore, R.D.; Shea, J.; Hutchinson, D.; Cannon, A. Coupled modelling of glacier and streamflow response to future climate scenarios. *Water Resour. Res.* **2008**, *44*, W02422. https://doi.org/10.1029/2007wr005956.
130. Brown, L.E.; Hannah, D.M. Spatial heterogeneity of water temperature across an alpine river basin. *Hydrol. Process.* **2008**, *22*, 954–967. https://doi.org/10.1002/hyp.6982.
131. Fleming, S.W.; Clarke, G.K. Attenuation of high-frequency interannual streamflow variability by watershed glacial cover. *J. Hydraul. Eng.* **2005**, *131*, 615–618. https://doi.org/10.1061/(asce)0733-9429(2005)131:7(615).
132. Gottfried, M.; Pauli, H.; Futschik, A.; Akhalkatsi, M.; Barančok, P.; Benito Alonso, J.L.; Coldea, G.; Dick, J.; Erschbamer, B.; Fernández Calzado, M.R.; et al. Continent-wide response of mountain vegetation to climate change. *Nat. Clim. Change.* **2012**, *2*, 111–115. https://doi.org/10.1038/nclimate1329.
133. Jacobsen, D.; Cauvy-Fraunie, S.; Andino, P.; Espinosa, R.; Cueva, D.; Dangles, O. Runoff and the longitudinal distribution of macroinvertebrates in a glacier-fed stream: Implications for the effects of global warming. *Freshw. Biol.* **2014**, *59*, 2038–2050. https://doi.org/10.1111/fwb.12405.
134. Brown, L.E.; Milner, A.M. Rapid loss of glacial ice reveals stream community assembly processes. *Glob. Change. Biol.* **2012**, *18*, 2195–2204. https://doi.org/10.1111/j.1365-2486.2012.02675.x.
135. Finn, D.S.; Räsänen, K.; Robinson, C.T. Physical and biological changes to a lengthening stream gradient following a decade of rapid glacial recession. *Glob. Change Biol.* **2010**, *16*, 3314–3326. https://doi.org/10.1111/j.1365-2486.2009.02160.x.
136. Robinson, C.T.; Thompson, C.; Freestone, M. Ecosystem development of streams lengthened by rapid glacial recession. *Fundam. Appl. Limnol.* **2014**, *185*, 235–246. https://doi.org/10.1127/fal/2014/0667.
137. Khamis, K.; Brown, L.E.; Hannah, D.M.; Milner, A.M. Glacier-groundwater stress gradients control alpine river biodiversity. *Ecohydrology* **2016**, *9*, 1263–1275. https://doi.org/10.1002/eco.1724.
138. Quenta, E.; Molina-Rodriguez, J.; Gonzales, K.; Rebaudo, F.; Casas, J.; Jacobsen, D.; Dangles, O. Direct and indirect effects of glaciers on aquatic biodiversity in high Andean peatlands. *Glob. Change Biol.* **2016**, *22*, 3196–3205. https://doi.org/10.1111/gcb.13310.
139. Finn, D.S.; Poff, N.L. Emergence and flight activity of alpine stream insects in two years with contrasting winter snowpack. *Arctic, Antarct. Alp. Res.* **2008**, *40*, 638–646. https://doi.org/10.1657/1523-0430(07-072)[finn]2.0.co;2.
140. Parker, B.R.; Vinebrooke, R.D.; Schindler, D.W. Recent climate extremes alter alpine lake ecosystems. *Proc. Natl. Acad. Sci. USA* **2008**, *105*, 12927–12931. https://doi.org/10.1073/pnas.0806481105.
141. Slemmons, K.E.H.; Saros, J.E.; Simon, K. The influence of glacial meltwater on alpine aquatic ecosystems: A review. *Environ. Sci. Process. Impacts* **2013**, *15*, 1794–1806. https://doi.org/10.1039/c3em00243h.
142. Carrivick, J.L.; Tweed, F.S. Proglacial lakes: Character, behaviour and geological importance. *Quat. Sci. Rev.* **2013**, *78*, 34–52. https://doi.org/10.1016/j.quascirev.2013.07.028.
143. Sommaruga, R.; Kandolf, G. Negative consequences of glacial turbidity for the survival of freshwater planktonic heterotrophic flagellates. *Sci. Rep.* **2014**, *4*, 4113. https://doi.org/10.1038/srep04113.
144. Sommaruga, R. When glaciers and ice sheets melt: Consequences for planktonic organisms. *J. Plankton Res.* **2015**, *37*, 509–518. https://doi.org/10.1093/plankt/fbv027.
145. Balseiro, E.; Souza, M.S.; Modenutti, B.; Reissig, M. Living in transparent lakes: Low food P:C ratio decreases antioxidant response to ultraviolet radiation in Daphnia. *Limnol. Oceanogr.* **2008**, *53*, 2383–2390. https://doi.org/10.4319/lo.2008.53.6.2383.
146. Laspoumaderes, C.; Modenutti, B.; Souza, M.S.; Navarro, M.B.; Cuassolo, F.; Balseiro, E. Glacier melting and stoichiometric implications for lake community structure: Zooplankton species distributions across a natural light gradient. *Glob. Change Biol.* **2012**, *19*, 316–326. https://doi.org/10.1111/gcb.12040.

147. Vinebrooke, R.D. The changing colours of mountain lakes in the Twenty-First Century. In *State of the Mountains Report 4*; Parrott, L., Robinson, Z., Hik, D., Eds.; Alpine Club of Canada: Calgary, AB, Canada, 2021; pp. 32–34, ISBN 9780920330814.