AGU PUBLICATIONS

Earth's Future

REVIEW

10.1002/2016EF000514

Toward mountains without permanent snow and ice

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Key Points:
- Deglaciation of low- to mid-latitude mountain ranges is likely to occur within this century
- Strong impacts on hydrology, erosion rates, sediment and nutrient flux, as well as water quality, aquatic habitat and biotic communities will result
- Far-reaching implications for human adaptation to a world of mountains without permanent snow and ice

Supporting Information:
- Supporting Information S1

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Citation:
Huss, M. et al. (2017), Toward mountains without permanent snow and ice, *Earth's Future*, *5*, doi:10.1002/2016EF000514.

Received 5 DEC 2016
Accepted 12 APR 2017
Accepted article online 24 APR 2017

Abstract The cryosphere in mountain regions is rapidly declining, a trend that is expected to accelerate over the next several decades due to anthropogenic climate change. A cascade of effects will result, extending from mountains to lowlands with associated impacts on human livelihood, economy, and ecosystems. With rising air temperatures and increased radiative forcing, glaciers will become smaller and, in some cases, disappear, the area of frozen ground will diminish, the ratio of snow to rainfall will decrease, and the timing and magnitude of both maximum and minimum streamflow will change. These changes will affect erosion rates, sediment, and nutrient flux, and the biogeochemistry of rivers and proglacial lakes, all of which influence water quality, aquatic habitat, and biotic communities. Changes in the length of the growing season will allow low-elevation plants and animals to expand their ranges upward. Slope failures due to thawing alpine permafrost, and outburst floods from glacier- and moraine-dammed lakes will threaten downstream populations. Societies even well beyond the mountains depend on meltwater from glaciers and snow for drinking water supplies, irrigation, mining, hydropower, agriculture, and recreation. Here, we review and, where possible, quantify the impacts of anticipated climate change on the alpine cryosphere, hydrosphere, and biosphere, and consider the implications for adaptation to a future of mountains without permanent snow and ice.

1. Introduction

Mountain environments have great topographic complexity, intertwined with linked physical and biological processes across steep vertical gradients. The mountain cryosphere (snow, ice, and permafrost) plays a critical role in these environments and is an important source of water to downstream regions. Seasonal and longer-term changes in the cryosphere regulate water, nutrient, and sediment supply to mountainous and downstream ecosystems and are crucial for multiple societal needs—agriculture, hydropower generation, drinking water supplies, recreation, and industry. Half of the world's population depends on mountain water, and anticipated future population growth is likely to further increase the pressure on water resources around the globe [*Beniston*, 2003].

Rising air temperatures over the past century have driven a reduction in the area and volume of glaciers, with deglaciation rates in high mountains accelerating in recent decades [*Bolch et al.*, 2012; *Rabatel et al.*, 2013]. A complete loss of glaciers in some low-latitude mountain ranges has already occurred [*Rabatel et al.*, 2013], accompanied by a shorter duration of seasonal snow cover [*Brown and Mote*, 2009] and widespread permafrost thaw [*Haeberli*, 2013]. As concentrations of greenhouse gases in the atmosphere continue to increase, average air temperatures are expected to rise further. Observations and model simulations point to particularly large temperature increases at high elevations, particularly at low latitudes [*Vuille et al.*, 2008;

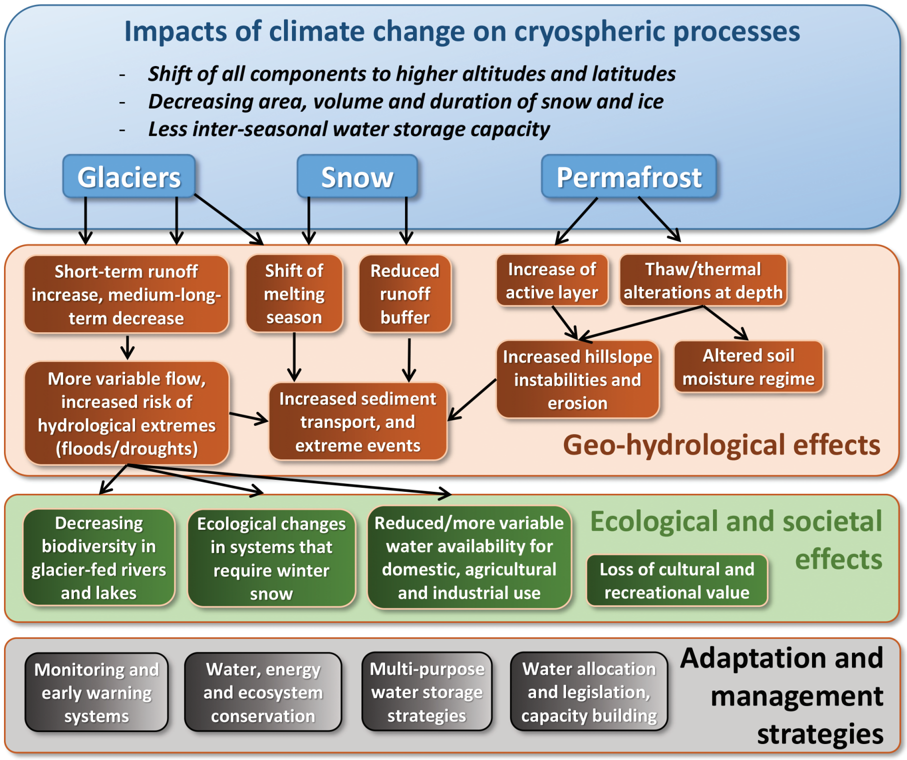

Figure 1. Summary of climate change impacts and process linkages within the mountain cryosphere.

MRI Working Group, 2015]. In addition, local and regional anthropogenic impacts, such as deposition of black carbon on snow and ice and the associated decrease in surface albedo, will have similar consequences [*Ramanathan and Carmichael*, 2008; *Xu et al.*, 2009]. Complex relations among cloud cover, solid and liquid precipitation, surface albedo, and net radiation will lead to further declines in glacier mass balance and the area of snow-covered terrain [*Painter et al.*, 2012]. As a consequence, we are in a transition phase from a world with glacierized mountains to a situation where permanent snow and ice cover is likely to be strongly reduced or even eliminated.

In this review paper, we assess the effect of the future decline of the mountain cryosphere, manifested in a series of cascading impacts on the natural and human systems that the cryosphere supports (Figure 1). Applying a global perspective, we consider the key hydrologic, geomorphologic, and ecological processes in which the mountain cryosphere plays a critical role. We quantify processes and mass fluxes that are presently relatively well understood and point to areas where a lack of quantitative measurements limits our understanding of potential future changes. Our review focuses on recent developments in quantifying present and future glacio-hydrological fluxes, as well as linking them to potential impacts on geomorphology, ecology, and society at the global scale, thus extending the scope of previous comprehensive reviews on this topic [e.g., *Beniston*, 2003; *Barnett et al.*, 2005; *Bolch et al.*, 2012; *Intergovernmental Panel on Climate Change*, 2013] on mountains and climate change.

2. Mass Fluxes Related to the Cryosphere and Mountain Hydrology

Figure 2 provides a schematic view of mountain systems and processes addressed in this paper. We quantify mass fluxes (F) and the mass of reservoirs (M) related to mountain hydrology at the global scale based on published literature. All fluxes are estimates that are subject to considerable uncertainties, which we do not discuss here. Below we summarize data, methods, and references used to quantify these fluxes.

We evaluate average total precipitation over the Earth's land surface area, except for Antarctica, for the period 1981–2010 based on several different data sets, including those of the Climatic Research Unit (CRU)

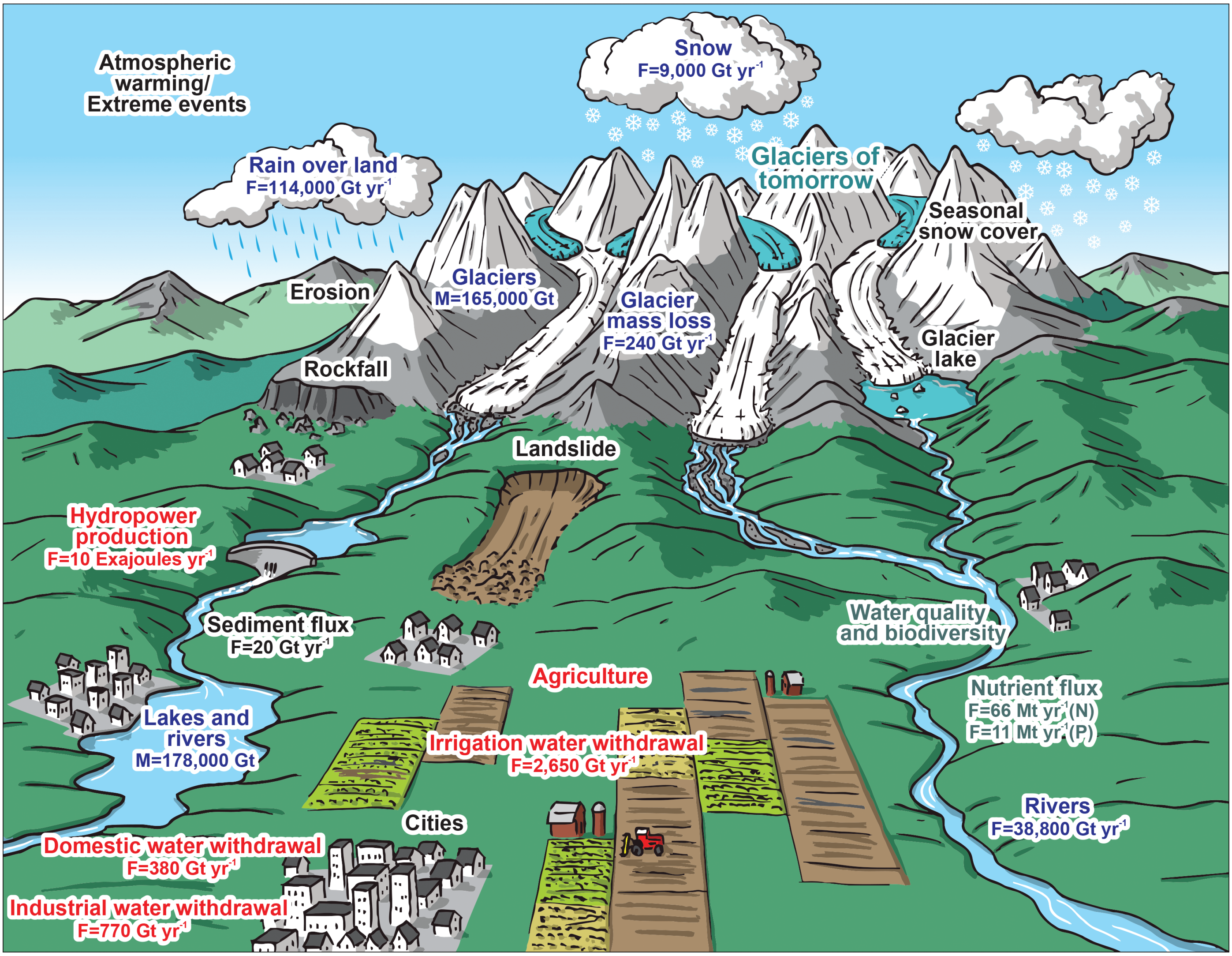

Figure 2. Schematic view of mountain systems and processes addressed in this paper. Estimates of mass fluxes (*F*) and the mass of reservoirs (*M*) refer to the global land surface.

[*Harris et al.*, 2014], the Global Precipitation Climatology Centre [*Schneider et al.*, 2011], and the University of Delaware [*Willmott and Matsuura*, 2001]. These data sets indicate a total precipitation flux over land of $F = 114{,}000\,\mathrm{Gt\,yr^{-1}}$, with a range of $\pm 9{,}000\,\mathrm{Gt\,yr^{-1}}$ among them. Solid and liquid precipitation has been separated using a threshold surface air temperature of 1°C. Temperature data have been provided by the CRU and the University of Delaware data set at monthly resolution and with areal cells of $0.5 \times 0.5°$, respectively. Snow precipitation over the Earth's land surface area except for Antarctica ($F = 9{,}000 \pm 500\,\mathrm{Gt\,yr^{-1}}$) also refers to the period 1981–2010.

The current mass of the roughly 200,000 glaciers on Earth, excluding the ice sheets in Greenland and Antarctica, is estimated to be in the range of $M = 127{,}000-217{,}000$ Gt, based on different studies [*Radić and Hock*, 2010; *Huss and Farinotti*, 2012; *Marzeion et al.*, 2012; *Grinsted*, 2013]. Glacier surfaces used to derive ice volume are provided by the Randolph Glacier Inventory [*Pfeffer et al.*, 2014]. The estimates correspond to about the year 2000. The rate of present glacier mass loss ($F = 240\,\mathrm{Gt\,yr^{-1}}$) refers to the period 2003–2009 [*Gardner et al.*, 2013].

The overall water volume of all lakes and rivers on Earth ($M = 178{,}000$ Gt) is based on a compilation by *Trenberth et al.* [2007]. Total annual runoff of all rivers on Earth into the ocean has been estimated by different authors based on river gauge observations, modeling, hybrid approaches, or the water balance [*Clark* *et al.*, 2015]. Average values for these approaches range from $F = 31,100$ to $F = 41,400$ Gt yr^{-1} [*Baumgartner and Reichel*, 1975; *Nijssen et al.*, 2001; *Fekete et al.*, 2002; *Clark et al.*, 2015]. Estimates of the total annual water withdrawal for irrigation range from $F = 2,200$ to $F = 3,800$ Gt yr^{-1}, mostly based on model-based approaches [e.g., *Oki and Kanae*, 2006; *Wisser et al.*, 2008; *Siebert et al.*, 2010; *Zhou et al.*, 2016]. Overall water withdrawals for domestic ($F = 380$ Gt yr^{-1}) and industrial ($F = 770$ Gt yr^{-1}) uses are based on *Oki and Kanae* [2006]. Total consumptive use of water by humans is estimated as $F = 1,380$ Gt yr^{-1} [*Flörke et al.*, 2013; *Zhou et al.*, 2016]. The total energy annually derived from hydropower production ($F = 10$ Exajoules yr^{-1}) is based on estimates made by *Goldemberg* [2000]. *Walling and Webb* [1996] estimated the cumulative annual sediment flux in all rivers globally as $F = 20$ Gt yr^{-1}, although the uncertainties in this estimate are large. Approximate global nutrient fluxes for nitrogen N ($F = 0.066$ Gt yr^{-1}) and for phosphorus P ($F = 0.011$ Gt yr^{-1}) are derived from a transport model by *Seitzinger et al.* [2005].

3. Past and Future Glacier Changes

Mountains accumulate snow, transform snow to firn and ice, and channel and regulate water runoff, which transports sediment and nutrients downstream. Glaciers, snow, and permafrost also store water in regions where other hydrological reservoirs, such as wetlands and aquifers, tend to be limited. A significant amount of water is currently stored in glacier ice in mid- to low-latitude mountain ranges, thus constituting a large hydrological reservoir in regions that shelter the majority of Earth's population (Table S1, Supporting Information). With a seasonal volume of around 9,000 Gt at the global scale (Figure 2), Earth's snow cover is an important element of the cryosphere that is linked to climate via a variety of feedback effects. *Brown and Mote* [2009] analyzed the impacts of climate change on the thickness and duration of snow cover in different mountain regions and found substantial effects on hydrology and ecosystems. In general, snow-to-rain ratios will decrease as air temperatures rise [*Knowles et al.*, 2006], and reductions in snow cover lead to positive feedbacks, enhancing the total radiative forcing of the Earth due to surface albedo changes [*Flanner et al.*, 2011].

Most mountain glaciers worldwide are strongly out of balance with climate and will lose up to one-third of their volume to achieve equilibrium state with current climate [*Mernild et al.*, 2013]. For the period 2003–2009, *Gardner et al.* [2013] estimated the mass loss of glaciers, excluding the ice sheets in Greenland and Antarctica, to be 240 Gt yr^{-1}, corresponding to an ocean water equivalent of 0.72 mm yr^{-1}, or about 30% of observed sea-level rise over this period. Despite the strong ice mass loss across all mountain ranges around the globe, a balanced mass budget has been reported for the early part of this century in some individual regions, for example the Karakoram [*Bolch et al.*, 2012; *Gardelle et al.*, 2012], which is likely due to changes in seasonality, atmospheric circulation, and enhanced winter snow accumulation on some glaciers [*Kapnick et al.*, 2014]. Projections using global circulation models (GCMs) for mountain ranges around the globe indicate major increases in air temperature over the next decades, but an inconsistent pattern for precipitation (Figures S1 and S2). Glacier models forced with GCM-output indicate continued ice loss in all regions [*Marzeion et al.*, 2012; *Giesen and Oerlemans*, 2013; *Radić et al.*, 2014; *Huss and Hock*, 2015]. By the end of the 21st century, relative losses in ice volume of between 30% (Alaska), around 50% (High Mountain Asia), and 80% (European Alps and low latitudes of the South American Andes) are expected, with considerable agreement among different models (Table 1). The total contribution to sea-level rise from mountain glaciers is estimated to be 90–220 mm by 2100 depending on the GCM and the emission scenario considered [*Marzeion et al.*, 2012; *Radić et al.*, 2014; *Huss and Hock*, 2015]. On time scales of a few centuries, an almost complete loss of mountain glaciers is possible if air temperatures continue to rise at current rates [*Levermann et al.*, 2013].

4. Assessing Changes in the Hydrology of Mountain Basins

Runoff from mountainous regions, except for those at low latitudes, is high during summer when other sources of water are often limited in the lowlands [*Barnett et al.*, 2005; *Viviroli et al.*, 2007]. Seasonal water releases from snow, ice, and permafrost are critical for maintaining hydrologic base flow, sediment and nutrient transport, and ecosystem structure and function, thereby providing vital environmental services and resources that are essential for human welfare both within mountains and much farther downstream [*Xu et al.*, 2009; *Immerzeel et al.*, 2010; *Viviroli et al.*, 2011].

Table 1. Calculated Relative Changes in Glacier Ice Volume Between About 2010 and 2100 for Selected Regions Based on Different Studies[a]

	Marzeion et al. [2012]	*Giesen and Oerlemans* [2013]	*Radić et al.* [2014]	*Huss and Hock* [2015]	Overall
Alaska	−28 ± 6%	−35 ± 10%	−25 ± 10%	−32 ± 11%	−30 ± 9%
Western Canada	−64 ± 7%	−45 ± 12%	−74 ± 9%	−76 ± 8%	−65 ± 9%
Scandinavia	−64 ± 10%	−28 ± 8%	−74 ± 24%	−81 ± 14%	−62 ± 14%
European Alps	−76 ± 11%	−88 ± 24%	−97 ± 13%	−77 ± 12%	−84 ± 15%
Caucasus	−53 ± 8%	−73 ± 20%	−75 ± 5%	−70 ± 11%	−68 ± 11%
Central Asia	−53 ± 8%	−54 ± 15%	−54 ± 15%	−54 ± 13%	−54 ± 13%
South Asia West	−39 ± 5%	−61 ± 17%	−41 ± 20%	−51 ± 11%	−48 ± 13%
South Asia East	−55 ± 7%	−88 ± 24%	−54 ± 15%	−66 ± 11%	−66 ± 14%
Sub-tropical Andes	−94 ± 7%	−66 ± 18%	−82 ± 5%	−79 ± 9%	−80 ± 10%

[a]The model results are based on the same emission scenario (Representative Concentration Pathway RCP4.5, except for *Giesen and Oerlemans* [2013], who use the A1B scenario) and the mean of 9–14 global circulation models. The results also are based on identical data on glacier area and distribution, but utilize different approaches to calculate glacier mass balance and retreat. Uncertainties refer to different global circulation models used to drive the glacier models.

To assess the present importance of the cryosphere for water availability in mountain catchments at low to mid-latitudes across all continents, we quantify the contributions of snow water equivalent (SWE) and effective rainfall (rain minus evapotranspiration) based on a combination of global remote-sensing data sets. This assessment is similar to the one made by *Kaser et al.* [2010], but relies on satellite-based observations of the relevant variables rather than climate re-analysis data. For the largest mountain catchments around the planet, we determine the annual totals of snow, glacier mass loss, rain, and evapotranspiration, allowing us to resolve the components of the water balance (Table 2). Data, methods, and uncertainties are described in detail in different studies [e.g., *Tedesco et al.*, 2004; *Bookhagen and Burbank*, 2010; *Bookhagen*, 2016] and are briefly summarized here.

4.1. Snow Water Equivalent (SWE)

Tedesco et al. [2004] provide daily grids of SWE (25 km resolution) based on microwave brightness temperatures using the AMSR-E/Aqua L3 product. Data are available continuously for the period 2002–2011 at the global scale. While there are considerable uncertainties in data derived from passive microwave monitoring at short temporal (i.e., daily) and spatial (at one to several pixels) scales, integration over seasons and entire catchments with drainage areas $>10^3$ km^2 is much more robust [*Smith and Bookhagen*, 2016]. Signal saturation at high snow depths might also affect the results [e.g., *Dong et al.*, 2005], but the effect of these uncertainties on our results at the basin-scale is considered to be limited.

4.2. Rainfall (R)

To estimate the distribution of annual rainfall (liquid precipitation) across all analyzed catchments, we use the Tropical Rainfall Measuring Mission (TRMM) 3B43V7 data set [*Huffman et al.*, 2007]. This data set provides precipitation estimates from multiple satellites, as well as gauge analyses for the period 1998–2012 at a spatial resolution of about 25 km × 25 km (0.25° × 0.25°). TRMM 3B43V7 overestimates single-event rainfall in mountain catchments [e.g., *Bookhagen and Burbank*, 2010; *Wulf et al.*, 2016], but provides reasonable estimates on larger spatial and longer temporal scales [e.g., *Carvalho et al.*, 2012; *Boers et al.*, 2015]. Although the TRMM 3B43V7 data set has been adjusted using precipitation gauges [*Huffman et al.*, 2007], its performance in remote high mountain environments remains difficult to assess because of limited availability of high-quality, long-term rain gauges in these areas.

4.3. Evapotranspiration (ET)

Data on effective evapotranspiration are provided by the MOD16 product [*Mu et al.*, 2007], which is derived from MODIS data at monthly to annual intervals with a spatial resolution of 1 km. The data set spans the

Table 2. Cryospheric, Hydrologic, and Demographic Characteristics of the Major Mountain Basins Analyzed in Figure 3[a]

River Catchment Unit	Basin Area (10^3 km^2)	Population Density (p. km^{-2})	Ice Volume (10^9 m^3)	Glacier Cover (%)	SWE + ΔM_g (10^9 m^3 yr^{-1})	R−ET (10^9 m^3 yr^{-1})	C (%)
Asia							
Yangtze	1,913	248	201	0.14	110	1,265	8
Tarim(e)	1,218	9	2,413	2.25	406	131	76
Junggar Basin(e)	1,038	11	125	0.28	364	144	72
Tibetan Plateau(e)	1,011	1	760	0.85	413	66	86
Ganges	948	399	793	1.30	81	797	9
Indus	859	175	2,559	3.13	262	313	46
Yellow	803	146	11	0.02	61	143	30
Mekong	773	67	29	0.06	29	699	4
Amudarya(e)	623	35	1,146	2.38	180	214	46
Brahmaputra	533	109	1,053	3.43	138	594	19
Lake Balkash(e)	415	12	157	0.68	189	95	67
Syrdarya(e)	326	61	60	0.38	113	92	55
Salween	265	26	62	0.48	47	124	28
Total	10,727	124	9,369	1.03	2,393	4,678	34
South America							
Amazon	5,888	4	62	0.03	4	8,050	0
Orinoco	934	11	0	0.00	0	1,639	0
Altiplano(e)	356	7	22	0.18	71	62	53
Central Andes	322	29	49	0.44	12	23	34
Magdalena	259	109	1	0.01	0	403	0
Total	7,760	11	135	0.05	86	10,178	1
North America							
Columbia	653	10	110	0.31	123	284	30
Colorado	628	12	0	0.00	76	86	47
Fraser	232	5	147	1.10	73	194	27
Total	1,513	14	257	0.28	272	564	33
Europe							
Danube	791	103	15	0.04	54	578	9
Rhine	164	298	19	0.21	11	97	10
Rhone	97	99	57	0.89	14	111	11
Po	73	221	16	0.45	18	79	18
Total	1,124	140	107	0.18	97	865	10

[a]Endorheic basins are marked with superscript (e). Population densities for 2000 are based on *Center for International Earth Science Information Network (CIESIN) et al.* [2005]. Snow water equivalent (SWE), glacier mass change (ΔM_g) total annual rainfall (R) and evapotranspiration (ET) are derived from remote sensing data, and the overall relative melt contribution C is calculated using equation (1).

period 2000–2010 and provides reasonable estimates for mountainous regions, for example, the Himalayas [*Bookhagen and Burbank*, 2010; *Wulf et al.*, 2016] and Tibet [*Chen et al.*, 2014]. We note that evapotranspiration is low in vegetation-free, high-elevation regions.

4.4. Glacier Mass Change (ΔM_g)

Annual glacier mass changes for large mountain regions (High Mountain Asia, European Alps, South American Andes, Coast and Rocky Mountains of North America) for the period 2003–2009 have been documented by *Gardner et al.* [2013] based on a combination of different remote sensing and in situ data sets. We have linearly distributed these mass changes over all individual catchments, assuming each glacier will exhibit the same rate of annual thinning as the mountain-range mean. Note that the sum of water issuing from glacier surfaces derives from glacier mass change, snow melt, and rain.

4.5. Contribution of Snow and Ice Melt to Runoff (C)

Combining the above data sets, we quantify to a first order the annual contribution of snow and ice (i.e., melt of the seasonal snow and annual glacier mass loss) to catchment runoff, defined as the sum of effective rainfall (R−ET) and runoff from seasonal snow and ice melt (SWE + ΔM_g). The relative contribution of the cryosphere to runoff is calculated as:

$$C = \left(\mathrm{SWE} + \Delta M_g\right) / \left(\mathrm{R} - \mathrm{ET} + \mathrm{SWE} + \Delta M_g\right) \quad (1)$$

We assume that all discharge is derived from the four components (SWE, ΔM_g, R, ET).

For the present analysis, we assume that the differences in the time periods covered by the individual data sets are negligible. The assessment is thought to be representative for the first decade of the 21st century. Our analysis does not account for groundwater retrieval [*Andermann et al.*, 2012; *Bookhagen*, 2012] and irrigation, which could cause water losses over large parts of the downstream basins.

Our data indicate that present glacier ice volume at low to mid-latitudes is concentrated in High Mountain Asia with smaller volumes in the European Alps, the Caucasus, the Coast and Rocky Mountains, and the Andes (Figure 3a, Table 2). Our simple method for estimating the cryospheric contribution to runoff in mountain catchments (equation (1)) indicates the importance of melting processes, and hence increased potential impacts of future climate change, in rather dry high-elevation regions. We find snow and ice melt contributions of 50% and more in some large-scale basins of High Mountain Asia, as well as in the Andes

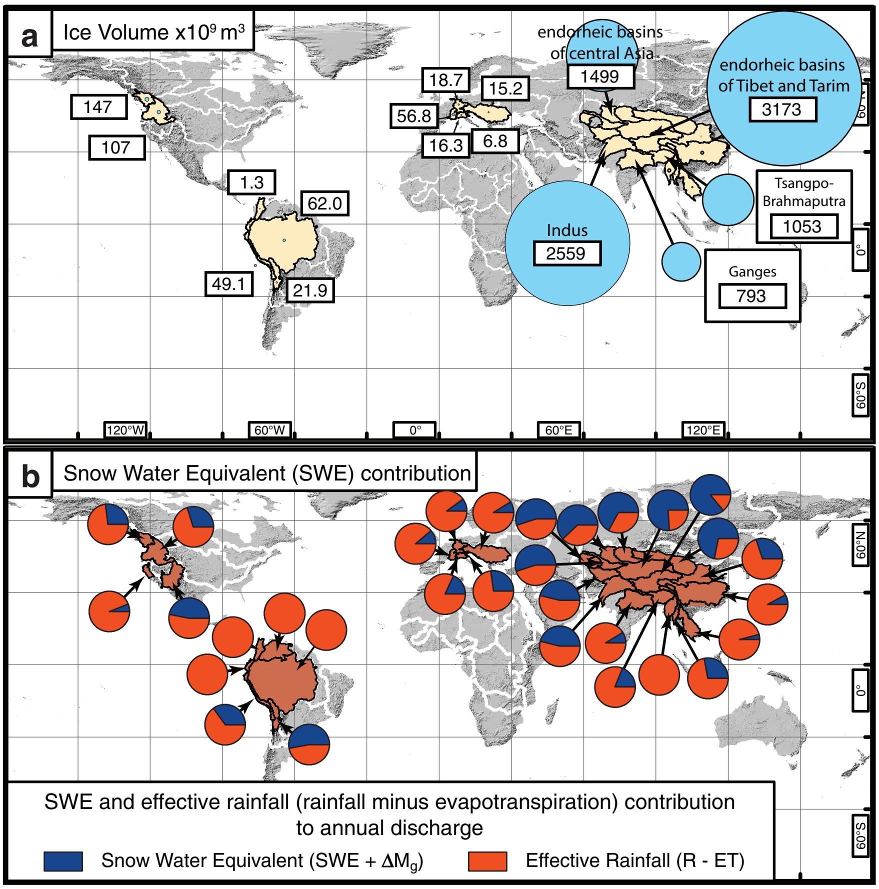

Figure 3. Hydrologic parameters of large mountain catchments. (a) Present-day glacier ice volume within large watersheds in mid- to low-latitude mountain ranges. Blue circles are scaled to ice volume. (b) Relative contributions of snow water equivalent and effective rainfall to total basin runoff. See Table 2 for more detailed information.

(Figure 3b, Table 2). These regions support large populations and also have experienced large population growth over the past decade (e.g., Indus, Table S1). Cryospheric contributions in regions influenced by monsoonal systems are generally small or negligible (e.g., Brahmaputra, Amazonas; Table 2). We note that across most basins the contribution from annual glacier mass loss (ΔM_g) is relatively small (mostly between 0.5% and 5%) compared to the melting of seasonal snow (SWE) (Table S2). However, annual glacier mass loss incompletely describes glacier contributions to runoff because the seasonal hydrological effect of glaciers is dominant [*Radić and Hock*, 2014]. These findings are consistent with earlier studies [e.g., *Schaner et al.*, 2012].

The importance of changes in snow and ice to downstream regions is determined by the hydrological regime of meltwater-fed streams (Figure 3b), ecological systems, and water demand, the last of which is dictated by population density and the importance of runoff to energy, agriculture, and other water-intensive sectors (Tables S1 and S2). Physical understanding and modeling suggest that changes in the type and temporal scale of runoff from glaciers depend on factors such as glacier size, elevation range, and hypsometry, the proportion of glacier cover in a catchment, and the way the glacier melt signal convolves downstream with other hydrological signals (i.e., groundwater, precipitation, and evapotranspiration). In some basins characterized by an arid summer climate, glacier meltwater accounts for up to 50% of melt season discharge [*Kaser et al.*, 2010; *Huss*, 2011; *Schaner et al.*, 2012; *Sorg et al.*, 2012]. Runoff from larger glaciers may increase for a few years to decades during the initial period of negative glacier mass balance, but will inevitably be followed by a decrease in the longer term [*Milner et al.*, 2009; *Mark et al.*, 2015]. Recent studies show that some watersheds with small glaciers in the Andes, North America, and Europe have already reached their "tipping points", also termed "peak water", and show decreasing annual discharge [*Baraer et al.*, 2012; *Frans et al.*, 2016]. Some local and regional-scale modeling studies confirm that runoff from glacierized catchments may increase for a few more decades, albeit with shifts in seasonal regimes [*Farinotti et al.*, 2012; *Immerzeel et al.*, 2013; *Bliss et al.*, 2014; *Lutz et al.*, 2014; *Ragettli et al.*, 2016]. However, a more comprehensive perspective across all glacierized regions of the world is still missing.

4.6. Future Changes in Mountain Hydrology

To investigate future changes in runoff from Earth's glaciers, we rely on model results from the Global Glacier Evolution Model (GloGEM) [*Huss and Hock*, 2015]. The model calculates distributed surface mass balance and glacier geometry changes in response to climatic forcing for each of the roughly 200,000 glaciers on the planet. GloGEM is forced with downscaled monthly air temperature and precipitation provided by 14 GCMs from the Climate Model Intercomparison Project CMIP5 [*Taylor et al.*, 2012]. The glacier model is calibrated using observed glacier mass changes [*Gardner et al.*, 2013] and is validated against in situ data from the World Glacier Monitoring Service [*World Glacier Monitoring Service (WGMS)*, 2012]. Initial ice thickness distribution is updated in annual time steps according to calculated surface mass balance (accumulation plus refreezing minus snow/ice melt). For each of the world's glaciers, GloGEM calculates the altitudinal distribution of surface mass balance at a vertical resolution of 10 m. This also allows the glacier's equilibrium line altitude to be derived now and in future (Figure 4).

Based on GloGEM, we calculate runoff from all presently glacierized surfaces within a drainage basin as the sum of snow/ice melt plus rain minus refreezing (i.e., all water exiting the glacier snout) [see *Radić and Hock*, 2014]. To ensure comparability of runoff volumes over time, we keep the catchment area over which future glacier runoff is evaluated constant during glacier retreat, even if the modeled ice area only covers part of the original basin toward the end of the century. We thus term calculated future runoff stemming from surfaces that are glacierized today as "headwater runoff" (Figure 4).

Figure 4 reveals important differences in the characteristics of glacierized watersheds around the world. Their area-elevation distribution defines ice cover and hence the response times of glaciers and potential future volume losses. In general, we find that headwater runoff continues to increase in the future in catchments with large ice volumes such as in northern North America, parts of the Himalayas, and Central Asia. In contrast, regions with smaller ice volumes at present such the Alps in Europe and the tropical Andes, face a decrease in runoff compared to current conditions. Our results are consistent with earlier findings on the importance of glacier meltwater to runoff [e.g., *Kaser et al.*, 2010; *Schaner et al.*, 2012], but extend the perspective globally and into the future and underline the importance of differences among individual basins. For instance, the contrast between individual basins is particularly strong in High Mountain Asia where the glacier melt season in the densely populated Indus, Ganges, and Brahmaputra basins coincides

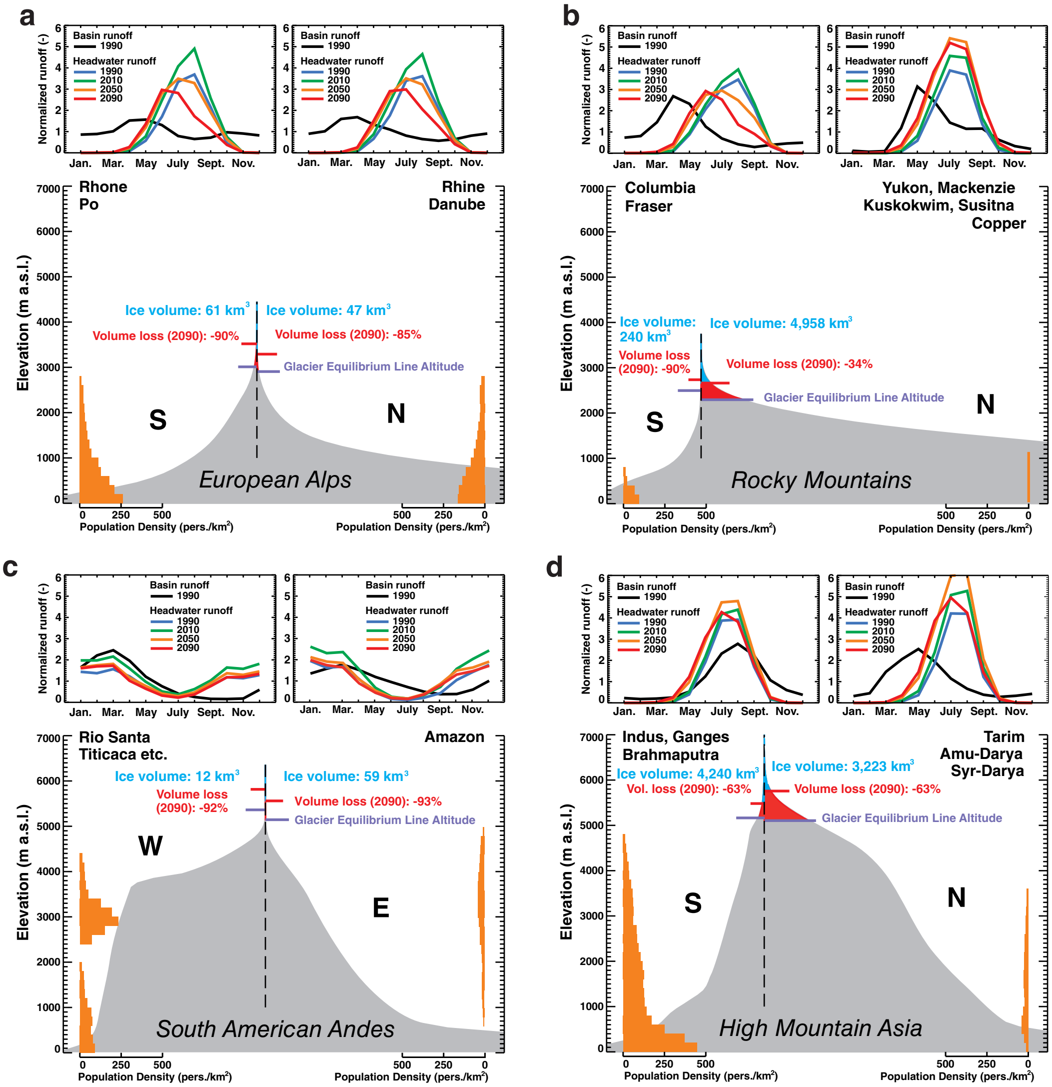

Figure 4. Cumulative land surface hypsometry [*Farr et al.*, 2007] of the world's major glacierized drainage basins: (a) European Alps, (b) western North America, (c) South America, and (d) High Mountain Asia, separated by the main weather divide (e.g., North/South). Present glacier ice volume and basin-averaged glacier equilibrium lines are shown as purple horizontal lines. The present-day (1980–2000) average equilibrium line altitude is based on a glacier area weighted mean. Also shown are modeled future changes in glacier volume and potential loss of glacier area (red), and reductions in equilibrium line altitude (red horizontal lines). Current population density as a function of elevation for each catchment indicates that people living in the lowlands depend on mountain water. Insets show both the observed runoff regime (period 1986–1995) of the respective basins (total monthly discharge normalized with average annual runoff), as well as present-day and future modeled runoff from glacierized areas based on *Huss and Hock* [2015]. Future changes in runoff due to a reduction in snow cover outside glaciers are not included in this analysis.

with high river runoff in the monsoon season, leading to small melt-to-discharge ratios (Figures 3b and 4, Table S2), whereas Central Asian watersheds are characterized by a summer-dry climate and streamflow is substantially enhanced by glacier melt in July and August.

Our global-scale assessment shows the major shifts in seasonal runoff regimes around the world that will result from the effect of reduced snow cover and ice. The results highlight the need to distinguish between the responses of individual basins following a transition toward mountains without permanent snow and ice. Seasonal shifts will be especially important in mid-latitude regions with moderate glacier volumes such as the European Alps and the mountains of western North America and accordingly will have substantial impacts on the hydropower sector, which is important in these regions. Water resource management will also be challenged in regions where glacier melt water is particularly important, notably seasonally dry regions such as parts of the tropical Andes and Central Asia (Figure 4). In addition, the decrease in snow and ice will likely increase the "flashiness" of mountain streams [*Tang et al.*, 2014]. Runoff will respond more rapidly to rainfall as glacier areas decrease, snow-to-rain ratios tend to become smaller, and the zero-degree line rises [*Knowles et al.*, 2006]. Runoff extremes are likely to occur more frequently in the coming decades, as are long-lasting droughts [*Collins et al.*, 2013]. It is important to note that these hydrological changes will become general in mountain regions, as climate models largely agree that temperature will increase worldwide (Figure S1).

5. Sediment Flux and Hazards in Mountain Areas

Erosion and sediment mobilization, transport, and deposition are fundamental processes in high-mountain regions, with potentially large impacts on society. Here, we review recent progress in understanding the physical processes and related impacts for a future without permanent snow and ice.

Sediment production rates from bedrock, normalized to unit area, are highest in the world's mountains [*Hallet et al.*, 1996]. Much research has been completed on erosion rates in glacierized catchments and on the interplay of climate, glaciers, topography, and tectonics [e.g., *Thomson et al.*, 2010; *Herman et al.*, 2013]. Glacial erosion rates are typically estimated from sediment yield data acquired from rivers and lakes, and range over four orders of magnitude around the world, from $<0.1\ \mathrm{mm\ yr^{-1}}$ to about $100\ \mathrm{mm\ yr^{-1}}$ [*Hallet et al.*, 1996; *Koppes and Montgomery*, 2009]. Recently, progress has been made in quantitatively linking glacial erosion rates to glacier sliding velocity [*Herman et al.*, 2015] and to ambient temperature, precipitation, and thus glacier thermal regime [*Koppes et al.*, 2015]. However, there is still limited understanding of the effects of glacier recession on erosion and sediment production. Major gaps in understanding include: (i) the effects of changes in the cryosphere on sediment production on decadal and centennial time scales, as opposed to longer ones and (ii) a comprehensive system perspective that considers the full cryosphere and geomorphic systems. Recent studies that adopt a landscape approach emphasize 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 [*Lane et al.*, 2016]. Case studies from a large glacierized catchment in the Alps (Monte Rosa, Italy) highlighted that slope instabilities linked to air temperature changes, glacier recession, and permafrost thaw in the late 20th century and the first decade of the 21st century caused an increase in the catchment-scale erosion from $1-2\ \mathrm{mm\ yr^{-1}}$ to about $50\ \mathrm{mm\ yr^{-1}}$ [*Fischer et al.*, 2013]. Important progress has been made in documenting the relations between alpine permafrost degradation and slope destabilization [*Krautblatter et al.*, 2013], but still little is known about their related effects on sediment production and flux at the catchment scale. Anecdotal evidence suggests that cryospheric changes in recent years may be driving geomorphic systems to tipping points, resulting in completely altered mass movement regimes with tremendous impacts on mountain communities, critical energy and transport lines, and hydropower infrastructure [*Huggel et al.*, 2012].

Extreme precipitation and runoff events play an important role in sediment mobilization and transport. 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, with volumes of up to $10^7-10^8\ \mathrm{m^3}$ of sediment delivered in single events and with significant impacts more than 100 km downstream [*Richardson and Reynolds*, 2000; *Korup and Tweed*, 2007]. Glacier lake outburst floods may become more frequent as glaciers thin and recede because new lakes will form and existing ones might grow. Many glacier-dammed lakes will be impacted by mass movements from adjacent destabilized mountain slopes [*Dussaillant et al.*, 2009; *Haeberli et al.*, 2016]. Global and regional climate models indicate that the frequency and intensity of future heavy precipitation events will scale with the rise in global mean temperature and cumulative total greenhouse gas emissions [*Seneviratne et al.*, 2016]. As indicated in the previous section, the synergistic effects of a higher frequency of extreme weather events and a reduced cover of snow and ice to dampen runoff peaks will result in a higher frequency of runoff extremes and thus likely produce higher sediment transport rates and associated impacts on downstream ecosystems and populations. Specifically, there will be substantial effects of enhanced sediment transport and deposition on water quality, aquatic habitat, flooding, infilling of hydropower reservoirs, turbine abrasion, and agricultural and infrastructural development [*Schaefli et al.*, 2007; *Finer and Jenkins*, 2012]. Hydropower infrastructure, especially in headwater regions of the Himalayas, Andes, and Alps, is particularly at risk from increased sediment flux and extreme hydro-geomorphic events [*Schaefli et al.*, 2007; *Wulf et al*., 2010; *Finer and Jenkins*, 2012].

The magnitude of these impacts is site- and catchment-specific and depends on the resilience and buffering capacities of the system, including the area occupied by glaciers and permafrost, basin hypsometry, groundwater systems, vegetation type and cover, and ecosystem types [*Bruijnzeel et al.*, 2011; *Buytaert et al.*, 2011; *Andermann et al.*, 2012]. The population and infrastructure within the catchment then determine vulnerability and potential damage. However, even within the best-monitored high-mountain catchments, there is still only a rudimentary quantitative understanding of hydro-geomorphic processes and their relation to climate change over relevant spatial and temporal scales. Yet, there is sufficient understanding and evidence to suggest that sediment processes need to be more strongly considered in water resource research and management in deglaciating mountain regions.

6. Aquatic and Terrestrial Ecology

A few organisms, mainly algae and microbes, live in snow and ice [*Anesio and Laybourn-Parry*, 2012]. Many more rely indirectly on the presence of snow and ice, and on their melt. Consequently, aquatic and terrestrial biological communities and processes in mountains are profoundly affected by climatic change, both related and unrelated to changes in the cryosphere.

Numerous studies have demonstrated upward shifts of species and communities in mountains [*Lenoir et al.*, 2008; *Chen et al.*, 2011; *Telwala et al.*, 2013]. Data from the extensive network of monitoring sites covered by the GLobal Observation Research Initiative in Alpine environments (GLORIA) have revealed an increase in the abundance of thermophilic (warm-adapted) plant species at high elevations and an upward shift of 2.5–2.7 m in the distribution limits of species from 2001 to 2008 [*Gottfried et al.*, 2012; *Pauli et al.*, 2012]. In the same period, mean species richness increased by a factor of 3.9 on boreal-temperate mountains, while it decreased by 1.4 on Mediterranean mountains, probably due to climatically driven reduced water availability in Southern Europe [*Gottfried et al.*, 2012; *Pauli et al.*, 2012]. A meta-analysis of worldwide treeline data shows that in 52% of sites, the treeline has been advancing uphill while only 1% reported treeline recession [*Harsch et al.*, 2009]. Warming conditions and advancing plant communities are reducing high alpine habitats and thus space for specialized high alpine species [*La Sorte and Jetz*, 2010; *Dirnböck et al.*, 2011]. However, climate-mediated range shifts are not necessarily related to changes in the cryosphere as such; they also happen in areas without glaciers. Studies of the ecological effects of the retreating cryosphere are still relatively few, so our understanding of these effects is far from complete and remains largely qualitative. Some trends, however, are well documented and unequivocal.

Rising air temperatures and the attendant shorter duration of snow cover directly influence the length of the growing season and the phenology of plant production and consumers, and thus the alpine-treeline ecotone [*Gottfried et al.*, 2012]. Higher temperatures also increase above-ground net primary production as long as there is no decrease in soil moisture that mediates soil nitrogen availability [*Berdanier and Klein*, 2011]. However, decreasing snow cover and an earlier growing season also expose wildflowers to frost damage [*Inouye*, 2008]. Early snowmelt decreases the mortality rates of some conifers such as *Pinus cembra*, whereas winter and summer drought reduce growth [*Oberhuber*, 2004]. Earlier loss of snowpack and more summer drought are already affecting tree species such as *Pinus contorta*, and at the same time increasing the risk of infestations by bark beetles [*Coops et al.*, 2010].

Receding glaciers and declining snow cover create new habitats and space that is colonized by early-succession, scree slope, and perennial clonal plants [*Chapin et al.*, 1994; *Cannone et al.*, 2008]. The presence of some keystone plants will be crucial for limiting soil erosion on steep slopes. However, some of these species (e.g., *Festuca valesiaca* in the Caucasus) already cope with dry conditions at their physiological limits [*Caprez et al.*, 2011], and increasing drought might limit the ability of such species to sustain this key ecosystem function [*Loreau et al.*, 2002]. Lack of water also inhibits soil microbial activity, thereby decreasing nutrient availability [*Stark and Firestone*, 1995] and primary production. Changes in the amount and seasonal availability of resources for consumers can potentially lead to mismatches, with cascading effects on food webs [*Miller-Rushing et al.*, 2010]. Initial increases in meltwater may elevate phosphorus and nitrogen inputs to downstream alpine wetlands and floodplains during high flows, enhancing the productivity of terrestrial communities [*Tockner et al.*, 2002].

The mountain cryosphere influences downstream aquatic ecosystems by governing flow regimes, channel stability, sediment concentration, water temperature, and nutrient supply, and is essential for supporting life during dry periods when snow and ice melt is the main water source. Due to harsh environmental conditions, macroinvertebrate communities in glacier-fed rivers are deterministic and dominated by a few specialized cold-water species close to the glacier [*Milner et al.*, 2001] where they find refuge from competitors [*Lencioni et al.*, 2015]. An increase in glacier meltwater runoff will lead to a colder and harsher aquatic environment, and possibly a downstream displacement of aquatic communities [*Jacobsen et al.*, 2014]. In the long term, however, glacier retreat will result in increases in stream temperatures in meltwater streams; sites that were next to the snout of Swiss glaciers in 1998 were 160–480 m farther away in 2009, and had a 2–4°C higher mean summer stream temperature [*Robinson et al.*, 2014]. The mean August temperature of an Alaskan stream increased from 2 to 18°C during from 1978 to 2003 as a result of the complete disappearance of its feeding glacier [*Brown and Milner*, 2012]. Such streams are quite quickly colonized by aquatic communities adapted to higher water temperatures [*Finn et al.*, 2010; *Robinson et al.*, 2014]; specific sites experience increasing species richness through time, tracking rising water temperature and other changing environmental conditions [*Milner et al.*, 2011].

Few datasets allow direct study of the long-term effects of glacier retreat on ecology in mountain streams [*Finn et al.*, 2010; *Milner et al.*, 2011]. However, “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 glacial retreat, point to similar results (Figure 5). They show that the richness of local aquatic macrofauna (alpha diversity) peaks at intermediate levels of glacial runoff [*Jacobsen et al.*, 2012; *Khamis et al.*, 2016]. Furthermore, the reduction and eventual loss of meltwater flow is predicted to: (i) reduce environmental heterogeneity at the watershed level, reducing species turnover among sites (beta diversity) [*Jacobsen et al.*, 2012; *Cauvy-Fraunié et al.*, 2015]; (ii) cause the loss of rare and specialized species from the regional species pool (gamma diversity) [*Jacobsen et al.*, 2012; *Quenta et al.*, 2016]; and (iii) elevated algal and herbivore biomasses, thus shifting ecological structure [*Cauvy-Fraunié et al.*, 2016]. In addition, genetic diversity within individual species decreases in headwater areas as glacier melt diminishes, because with less isolation individuals intermix to a greater degree when mating [*Finn et al.*, 2013]. Reduced meltwater also has been shown to reduce migratory corridors for anadromous fish [*Milner et al.*, 2009]. Finally, a shorter duration of snow cover shifts life cycles. For example, earlier emergence [*Finn and Poff*, 2008] and increased production of stream insects [*Schütz et al.*, 2001] may benefit terrestrial invertebrates, reptiles, and birds.

An earlier onset of melting of lake surface ice will affect the heat content, underwater light climate, temperature regime, oxygen regime, and mixing of lakes [*Melack et al.*, 1997]. Indirectly, changes in melting in the catchment can affect downstream lakes through changes in water level, turbidity, water chemistry,

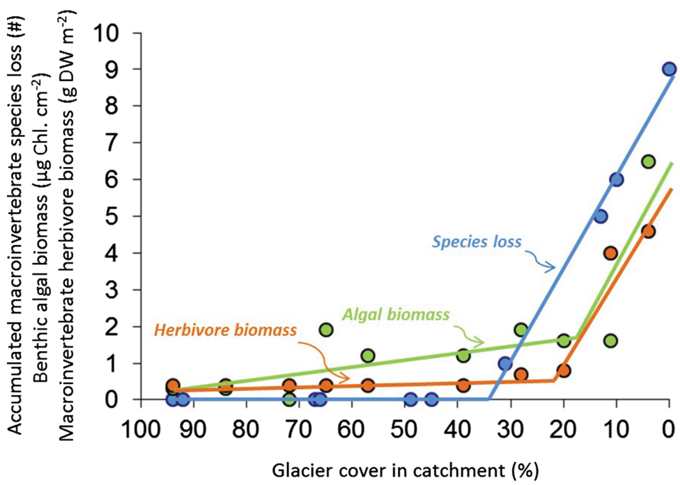

Figure 5. Ecological features of small streams with different percentages of glacier cover in a watershed draining Antisana volcano in the Ecuadorian Andes. *Accumulated species loss* is the number of macroinvertebrate species with a preference for streams influenced by glacier meltwater that are lost from the regional species pool at sites with declining glacier cover. *Algal biomass* is the amount in chlorophyll units (µg cm^{-2}) of algae (periphyton) in stream channels. *Herbivore biomass* is the amount in g dry-weight m^{-2} of the functional feeding group of macroinvertebrates that primarily live on the algae. Data from *Jacobsen et al.* [2012] and *Cauvy-Fraunié et al.* [2016].

input of nutrients and other solutes, and the timing of this input. These changes will individually and synergistically strongly affect benthic and pelagic communities [*Parker et al.*, 2008; *Slemmons et al.*, 2013]. For example, suspended sediment loads from glacier meltwater increase turbidity, which protects zooplankton from ultraviolet B radiation, but also limits light penetration for phytoplankton production and obstructs feeding by zooplankton [*Sommaruga*, 2015]. Due to glacier retreat, proglacial lakes are currently forming at a high rate in most arctic and alpine areas of the world [*Carrivick and Tweed*, 2013]. Typically, these lakes are initially dominated by microbes and devoid of higher life [*Sommaruga and Kandolf*, 2014]. Later, they are colonized by algae, protozoans, and invertebrates, and food webs form [*Sommaruga*, 2015]. As glaciers disappear, or lakes lose connection to them, lake transparency increases, affecting the fitness of species with high demands for phosphorus and increasing ultra-violet radiation and visual predation pressure [*Balseiro et al.*, 2008; *Laspoumaderes et al.*, 2013].

7. Societal Adaptation and Management Strategies

The current transient state of climate, together with future greenhouse gas emissions, will ensure an irreversible loss of glaciers, permafrost, and permanent snow in some mountain ranges, irrespective of future mitigation undertaken by society to moderate climate change. Adaptation to the loss of snow and ice will thus be required in all mountain regions [*Field et al.*, 2012]. Yet, physical, ecological, and socio-economic systems in mountains are multi-faceted, and behave and respond in ways that differ considerably across mountain watersheds [*Das et al.*, 2011]. These systems are typically more complex than can be fully captured by historic observations or simple predictive models. This complexity poses major challenges to adaptation [*Buytaert et al.*, 2010]. On the other hand, general trends in the response of some sub-systems (e.g., the water cycle) to rising air temperatures are relatively well understood, allowing strategies to be developed for the future. A region's sustainability will depend on the capacity to cope with the challenges of climate change, and this will be affected by multiple factors such as the prevailing governance structure, the ecological integrity of the region, and justice accessing local resources [*Schneider et al.*, 2015]. Society should focus on an adaptive governance approach, with continuous learning and flexibility as key aims [*Folke et al.*, 2005]. Information about how systems respond to environmental and human stressors, and the ability to adapt by changing direction are of first-order importance [*Pahl-Wostl*, 2009].

In specific catchments of the European Alps, for example, unprecedented mass wasting related to permafrost degradation has strongly elevated sediment fluxes, requiring a re-evaluation of transport routes and relocation of mountain communities under economic, touristic, energy, and social pressures [*Huggel et al.*, 2012]. In the Andes of Peru, rock and ice avalanches from steep slopes have impacted lakes that formed as glaciers receded, triggering localized disastrous downstream floods and debris flows. At the same time, shrinking glaciers change water availability for local and regional economies during the dry season [*Bury et al.*, 2013]. Emerging adaptation efforts should therefore be focused on water retention measures that address water availability issues and reduce the risk of outburst floods. Nevertheless, actual water usage patterns are more profoundly impacted by societal forces than climatically mediated hydrological supply, underscoring the need to adopt a socio-hydrologic framework to evaluate legal, economic, political, cultural, and social drivers [*Carey et al.*, 2014].

Multiple-use water storage and distribution strategies, for example, systems that meet both irrigation and drinking water needs, will play a key role in future water resource management and in helping communities offset for decreasing storage of water in snow and ice with associated disruptions in the seasonality of flow. Traditionally, water storage infrastructure has been built for single uses (e.g., hydropower, flood control, or irrigation), but changes in seasonal supply and demand will require management for multiple uses. This reassessment requires consideration of the socio-political context with considerable lead-time [*Clarvis et al.*, 2014; *Schneider et al.*, 2015]. Given the importance of temporal and spatial scaling issues and system complexity, the most effective strategies will emerge from regional planning, knowledge sharing, and compromises among the competing water needs of multiple users as well as ecosystem needs. Furthermore, in less developed regions, capacity building, training, and international cooperation continue to be important, and corresponding international environmental policies need to be strengthened.

Limitations to our understanding of mountain environments, as well as the challenges of adaptive management, have implications for future research priorities. There is a compelling need to improve our understanding of environmental and ecological systems in mountain regions. We have only a limited quantitative comprehension of these systems and their interactions. A stronger knowledge base can better inform sustainable decision-making, which requires a system approach grounded in understanding interactions, impact cascades, and thresholds in the physical and ecological environments. We thus recommend concerted and collaborative efforts to acquire multidisciplinary observations in representative catchments of distinct regions. Ideally, these should be guided by common protocols, similar to the GLORIA network [*Grabherr et al.*, 2000; *Pauli et al.*, 2005; www.gloria.ac.at]. Furthermore, we advocate research programs that involve the full spectrum of stakeholders in order to take into account local experience and views about possible future developments [e.g., *Valdivia et al.*, 2010]. Creating a relevant base of evidence for adaptive governance should foster development of distinct geographic solutions and approaches that may differ among regions because of different social, cultural, and economic interests. A key issue for inhabitants of mountains experiencing climate and other stresses is their resilience in the face of constantly changing conditions and their ability to adapt and maintain basic functions and services [*Folke et al.*, 2010].

Based on our analysis, which has involved both qualitative and quantitative assessments of the directions of change in the mountain cryosphere, it is clear that many important questions remain, requiring more extensive research on specific aspects of the physical, biological, and socio-economic environments of mountain regions. We also recognize major challenges that transcend traditional disciplinary science, requiring further research at the science-society interface.

Acknowledgments
All data are available on request from the first author. We thank the International Geosphere-Biosphere Programme (IGPB), Stockholm and the Mountain Research Initiative (MRI), Bern, for financial support.

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