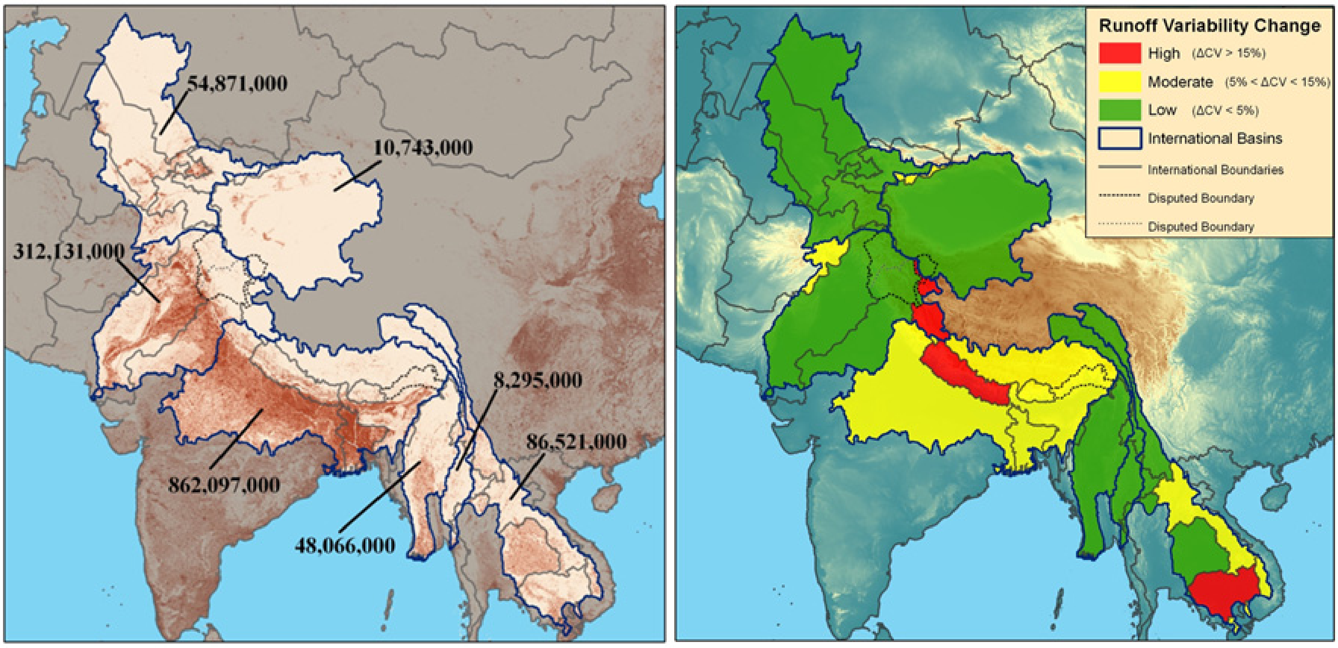
Glaciers as a water resource

Mountains as Water Towers of the World

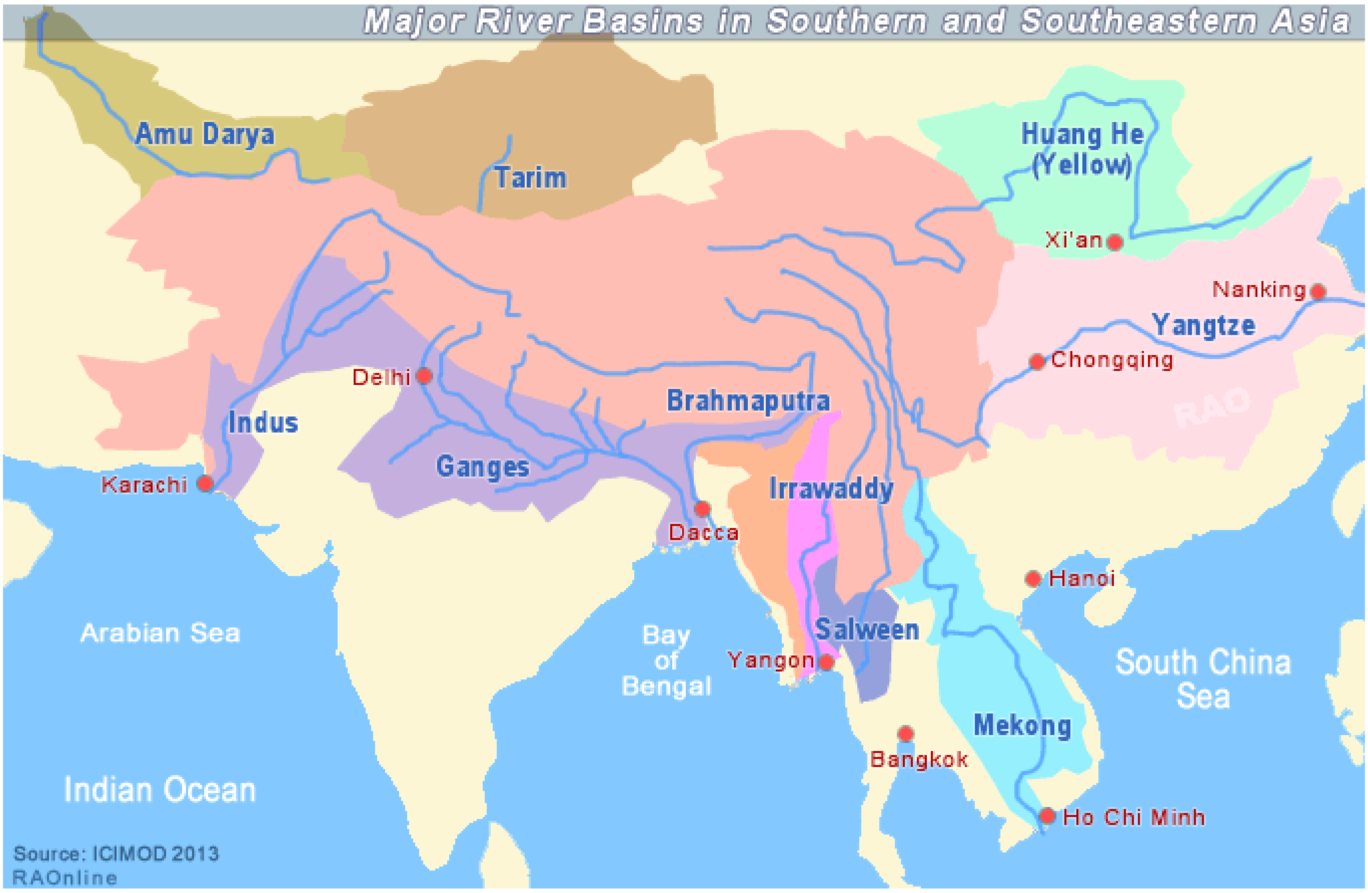
In many mountainous parts of the world with a seasonal rainfall, glaciers are a reliable water resource in the dry season. Mountains could be called the "Water Towers of the World"[1], providing water from glacier melt and orographic rainfall to lowland regions.

Glacierised drainage basins cover 26% of the global land surface outside of Greenland and Antarctica, and are populated by almost one-third of the World's population[2]. Upland areas (above 2000 m above sea level) in southeast Asia supply the five basins of the Indus, Ganges, Yellow, Brahmaputra and Yangtze rivers, providing water to 1.4 billion people (over 20 % of the global population).



The Himalayan river basins and the number of people living in each one.

(Source: Redrawing the map of the world's international river basins)



High Mountain Asia river basins

(source: https://www.raonline.ch/pages/np/visin/np_rivers1301.html)

Glacier meltwater and runoff

Glacier meltwater and runoff contribute to and module downstream water flow, affecting freshwater availability for irrigation, hydropower, and ecosystems[3].

Glacier runoff is typically seasonal, with a minimum in the snow-accumulation season, and a maximum in the melt season. This meltwater can compensate for seasons or years with low streamflow or droughts in downstream regions[4].

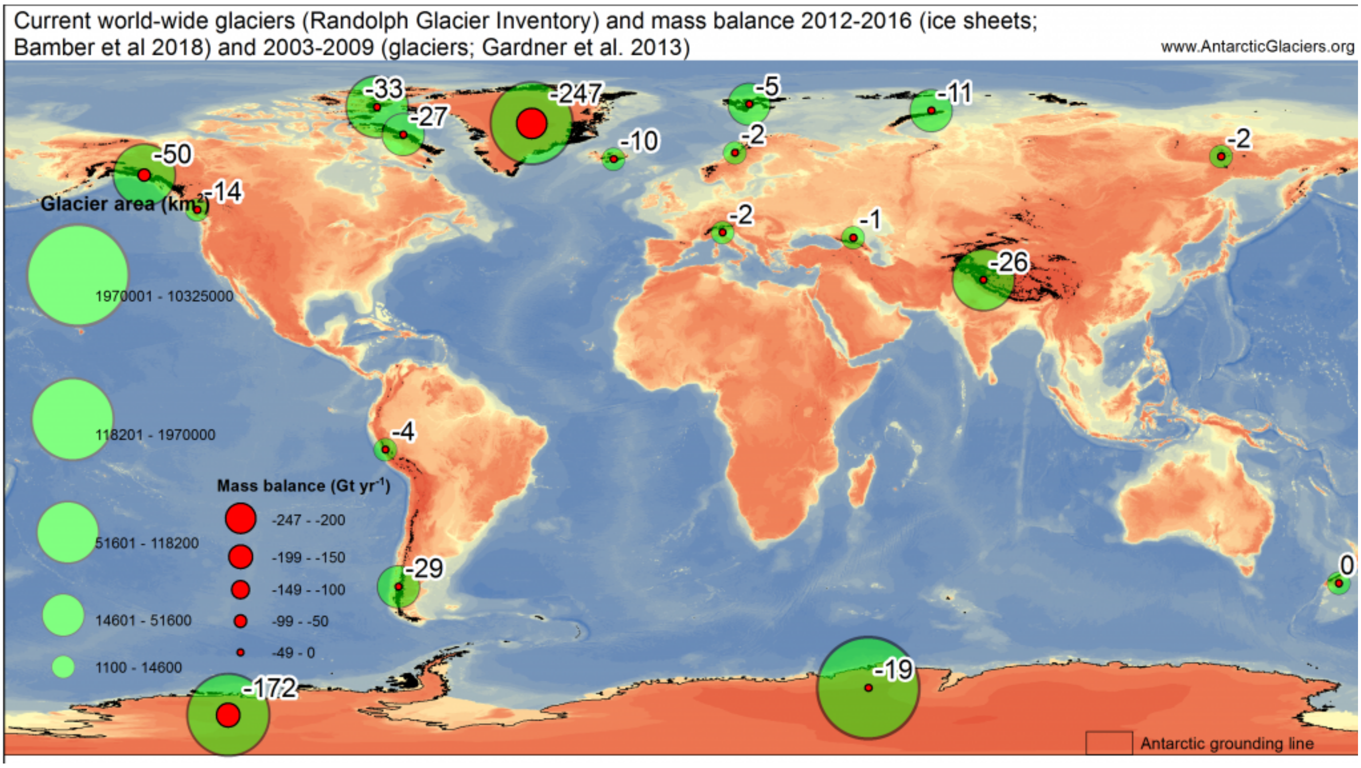
Mountain glacier and lake in Peru

In this video, I discuss global glacier volume and how glaciers are shrinking worldwide, and the impacts of this on global water supply (suitable for A-Level Geography or Post-16 or undergraduate students).

Global glacier recession

Mountain glaciers around the World are currently shrinking[5-7], and this is expected to continue throughout the next century. Globally, glaciers are shrinking by 227 ± 32 gigatonnes per year[8], enough to raise global sea levels by 0.63 ± 0.08 mm per year.

The areas shrinking fastest are in north America (-50 gigatonnes per year), northern Arctic Canada (60 gigatonnes per year), the Himalaya region (26 gigatonnes per year), and South America (29 gigatonnes per year)[8].



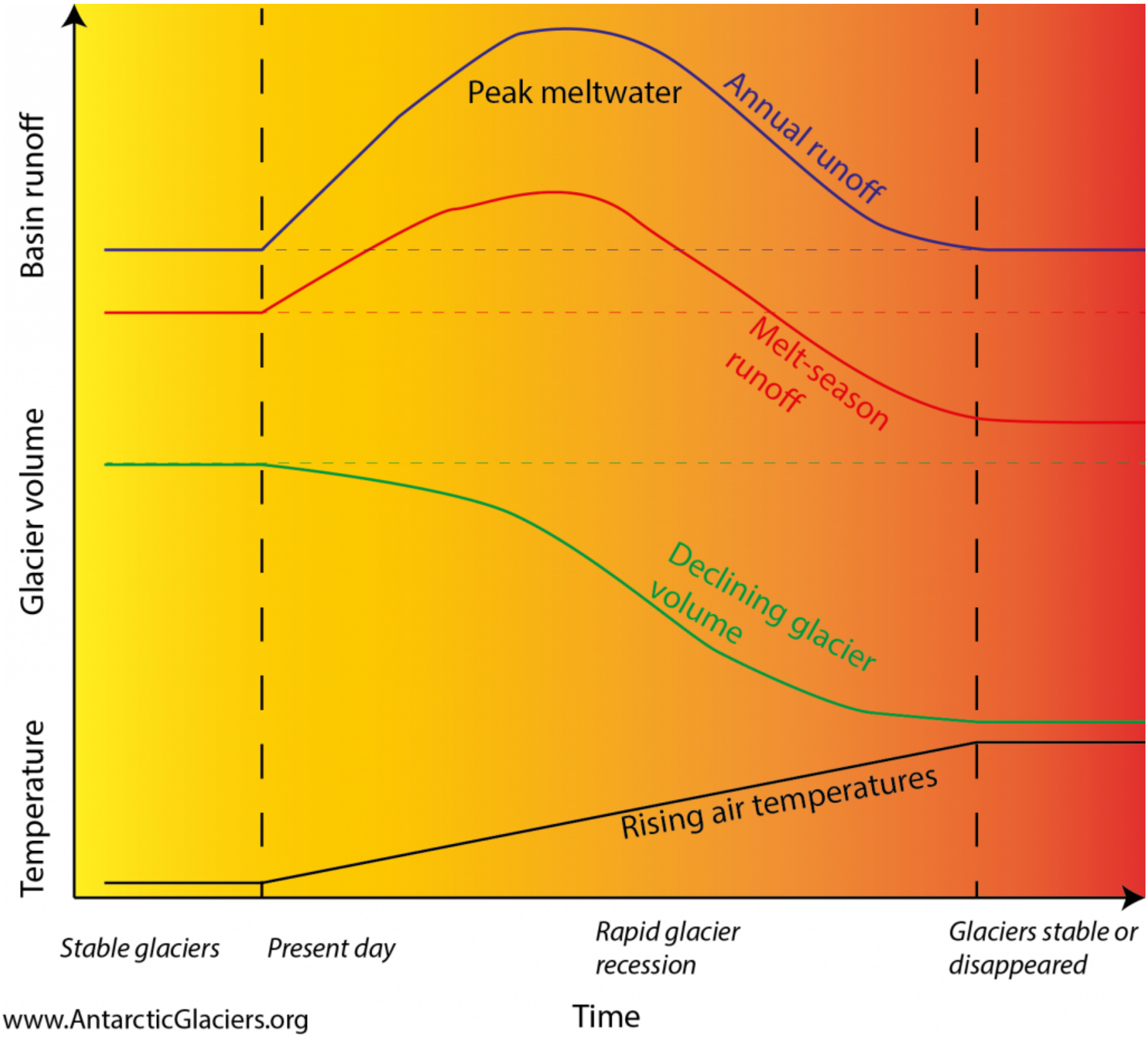
World glaciers and ice sheets mass balance. Glaciers are shown in black. Green circles show glacier area, red circles are how much ice is lost annually.

Glacier “Peak meltwater”

As glaciers shrink, meltwater is released from storage within the glacier. Annual meltwater therefore increases, until a maximum is reached[3,9]. This maximum has been called ‘Peak Meltwater’.

After Peak Meltwater, runoff decreases as smaller glacier volumes can no longer support rising meltwater volumes. As the glacier retreats and disappears, annual runoff from direct precipitation may return to something like the original value, as water is no longer stored as snow. However melt-season runoff may decline substantially, as the glacier no longer acts as a reservoir. Seasonality of water availability may therefore increase, leading to droughts in dry years or dry seasons.

Essentially, as the glaciers shrink, they provide less and less melt water from long-term storage, which impacts seasonal freshwater availability[3].



Peak Meltwater and glacier recession under a warming climate.

Adapted from Huss and Hock (2018) and Rowan et al. (2018).

The degree to which glacier runoff contributes to downstream meltwater varies according to the basin, with glacier contributions being as much as 25% of the annual water budget. In many of these basins, peak meltwater is expected to have passed (e.g., Ref. [10]), or will be passed in the next 20-30 years (e.g. Ref. [11]). Ultimately, some projections suggest that up to half of the world's population could be living in water scarcity by 2100 AD[12].


Meltwater stream on Mendenhall Glacier, Alaska. From: Gillfoto, Wikimedia Commons

Global scale peak meltwater?

A recent study by Huss and Hock (2018, *Nature Climate Change*) computed glacier runoff changes for the Earth's 56 large-scale (>5000 km^2) glacierised drainage basins with at least 30 km^2 of ice to 2100 AD, and analysed the effect of glacial recession on streamflow.

In half of the basins, peak meltwater has already been reached. In the remaining basins, the modelled annual glacier runoff continues to rise until the maximum is reached, and then runoff declines. Peak water tends to occur later in basins with larger glaciers and higher ice-cover fractions[3].

The researchers used a glacier model and climate model outputs forced by three different emissions scenarios, with peak emissions occurring at 2020 AD (RCP 2.6), 2050 AD (RCP 4.5) and after 2100 AD (RCP 8.5)[3]. RCP 2.6 is the closest scenario to the targets of the Paris 2015 climate agreement. Projected temperature increases between 1990-2010 and 2080-2100, range from 1.6 ± 1.1°C (RCP 2.6) to 5.4 ± 2.2°C.

Between 2010 and 2100 AD, glacier volume in the 56 investigated basins was projected to decrease by 43±14% (RCP 2.6), 58±13% (RCP 4.5) and 74±11% (RCP 8.5). For the mid-range RCP 4.5, glacier volume reductions in the individual basins ranged from 37 to 99%[1].

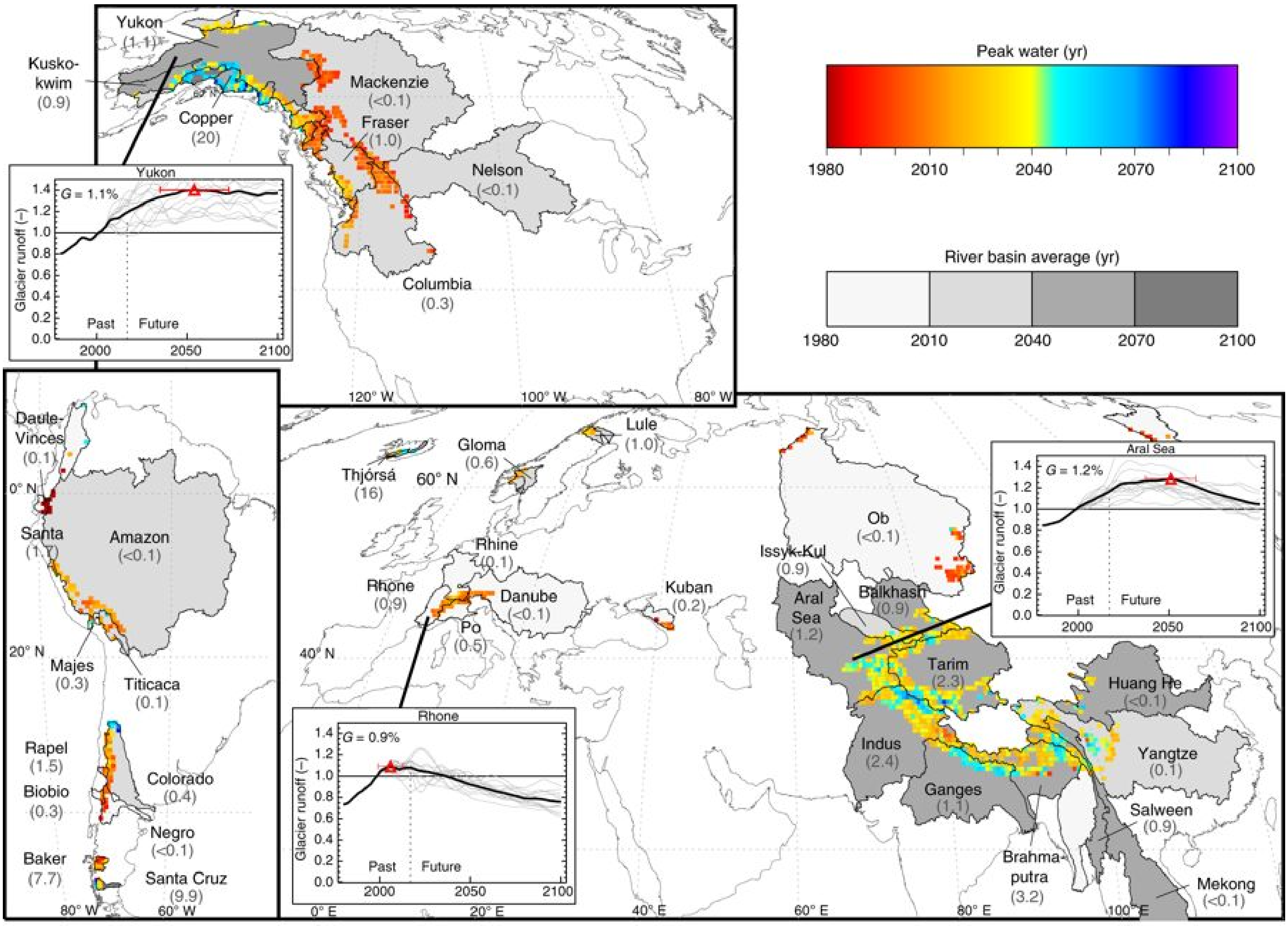
Reaching Peak meltwater

Peak meltwater has already been reached in 45% of the basins (year 2017 AD), but annual runoff is expected to continue to rise beyond 2050 AD in 22% of the basins. Basins with larger glaciers and high glacier cover (e.g. Susitna, Jökulsá) tend to reach peak meltwater towards the end of the twenty-first century.

In basins dominated by small glaciers (e.g. western Canada, central Europe, South America), peak meltwater has already passed and meltwater will decline over coming decades.

In most basins fed by High Mountain Asia (Aral Sea, Indus, Tarim, Brahmaputra), annual glacier runoff is projected to rise until the middle of the century, followed by steadily declining glacier meltwater runoff thereafter[3].

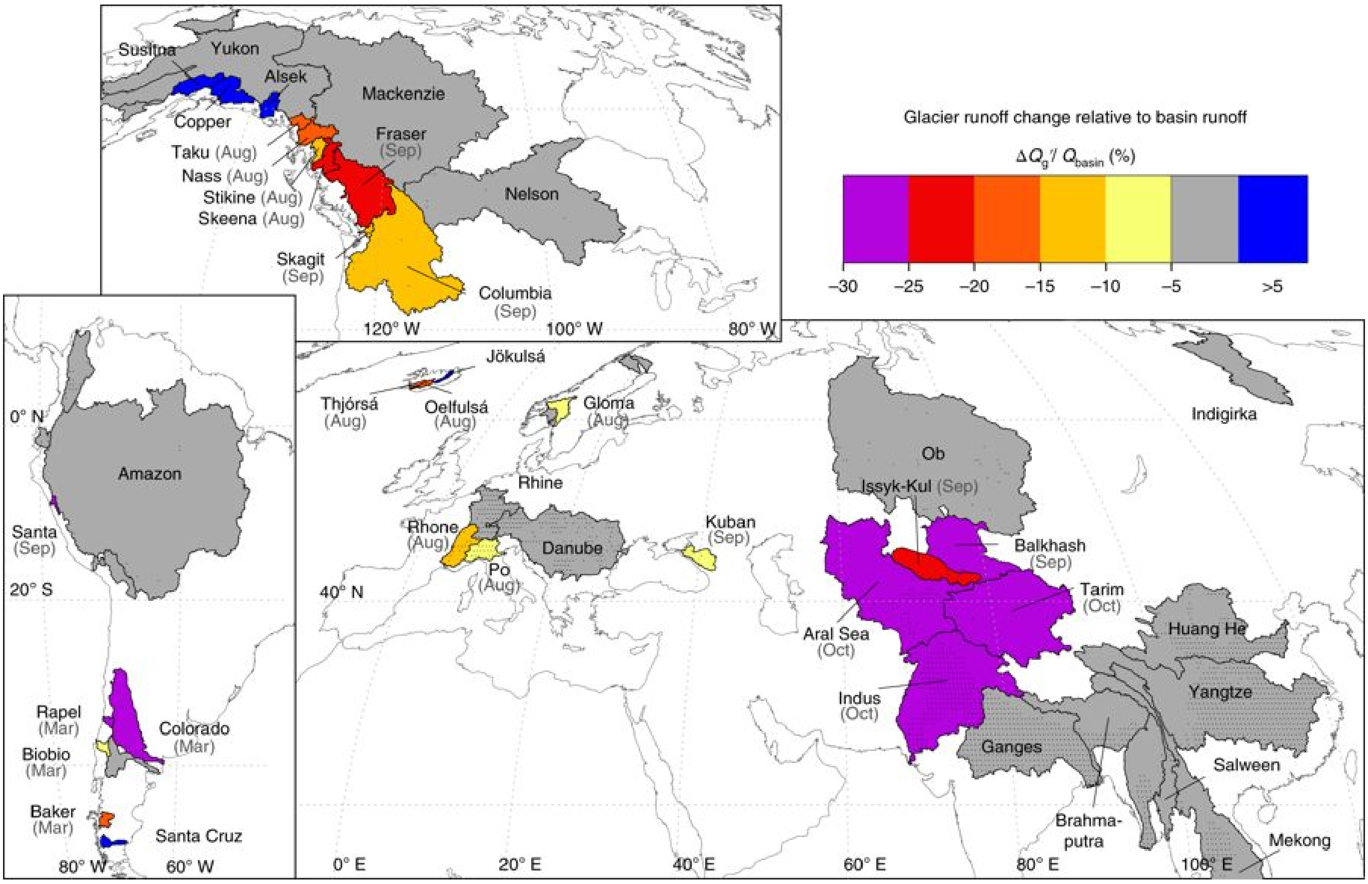
By the end of the twenty-first century, the seasonal glacier runoff maximum is reduced in 93% of the basins compared with the 1990-2010 average, and runoff is less concentrated during the melt season.



Colours show the modelled year of peak water computed from 11-year moving averages of annual glacier runoff from all the glaciers located in the 56 investigated drainage basins, aggregated in 0.5 × 0.5° grid cells. Peak water is also shown with grey scales for all the macroscale basins, classified in 30-year intervals. The results refer to runoff from the initially glacierized area, and are based on the multimodel mean of 14 GCMs and the RCP4.5 emission scenario. The numbers in brackets below the basin names refer to basin glacierization in per cent. The insets show the modelled annual glacier runoff normalized with the average runoff in 1990–2010 for three selected basins. Triangles depict peak water (± standard deviation), thin lines show results for individual GCMs and *G* denotes the percentage ice cover. From Huss and Hock, 2018

In 19 of the 56 basins, the glacier runoff change between 2000 and 2090 AD accounts for at least one melt-season month with a reduction in runoff of at least 10% (i.e. glacier runoff reduction exceeds 10% of the basin runoff). This is sufficient to cause water scarcity in these basins.

The most significantly affected basins are in High Mountain Asia (Aral Sea, Indus, Tarim, Balkhash), Peru (Santa), South America (Colorado, Baker, Santa Cruz), and North America (Fraser, Skeena, Taku, Nass)[3].



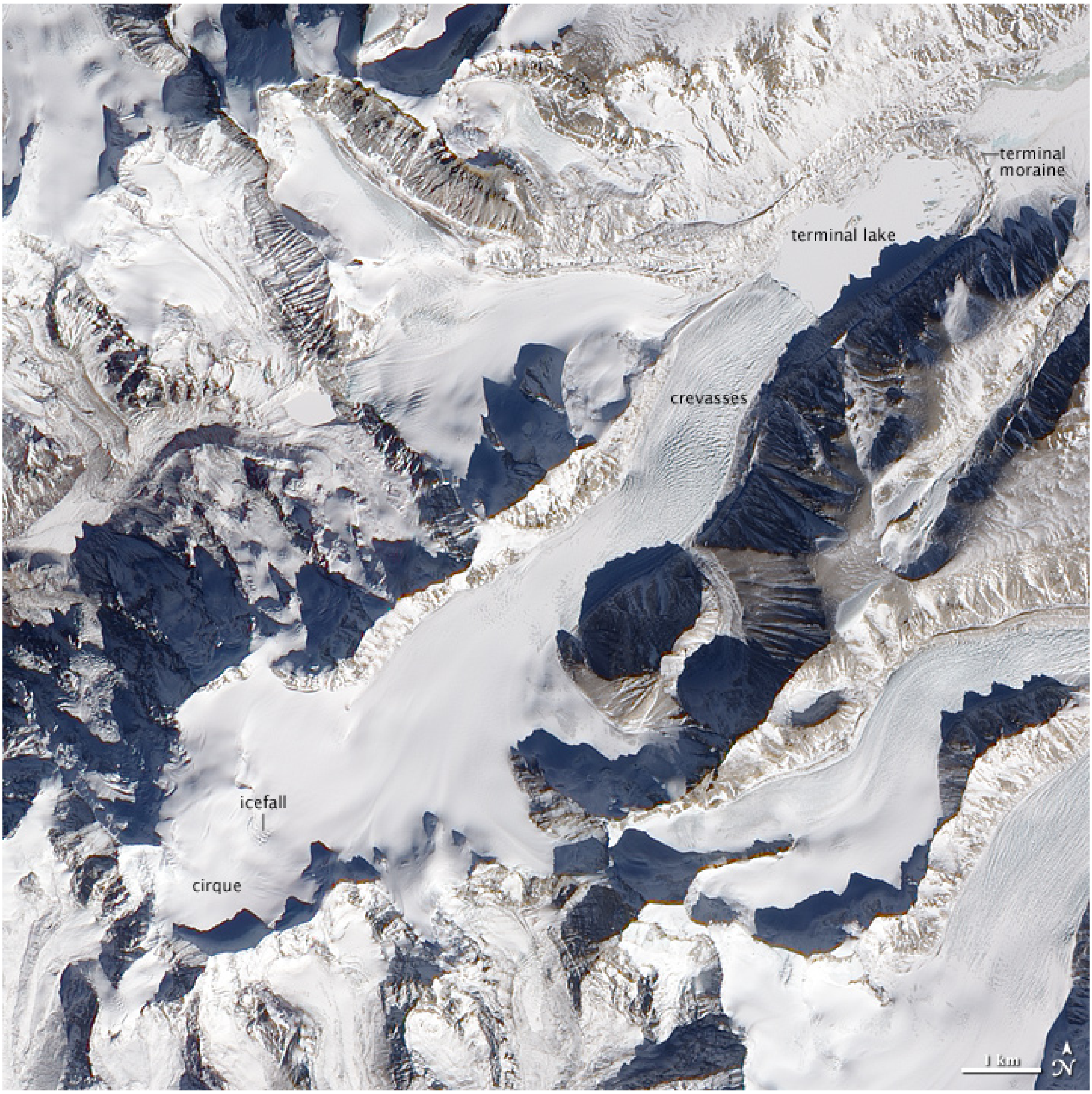
The ratio of glacier runoff change to basin runoff is evaluated for the period July to October (January to April for the southern hemisphere, and throughout the year in the tropics). For basins with substantial glacier runoff decreases in at least one month, the ratio refers to the month (given in brackets below the basin names) with the largest reduction in glacier runoff. Basins with negligible glacier impact ($|\Delta Q'g/Q\text{basin}| < 5\%$) are shown in grey, and the remaining basins, which show glacier runoff increases that exceed 5% in at least one month, in dark blue. The results refer to multi-GCM means and RCP4.5. Small dots refer to population density > 100 km^{-2} on a 0.5 × 0.5° grid as an indicator for potential downstream socio-environmental impacts.

Case study: Glaciers and water resources in the Himalaya

In the Himalaya, Karakorum and Hindu Kush mountains, millions of people rely on the 90,000 glaciers as a water resource[9]. These glaciers form the headwaters of the Indus, Ganges and Brahmaputra rivers. Glaciers here are highly sensitive to climate change, and are rapidly shrinking[7,13]. The developing countries in these catchments use this water for agriculture and hydropower, and are vulnerable to changes in their water supply[14].

The contribution of glaciers to runoff varies in each basin, ranging from 18.8% in the Dudh Koshi catchment (a major tributary to the Ganges), to 80.6% in the Hunza catchment, which drains into the Indus basin[9].

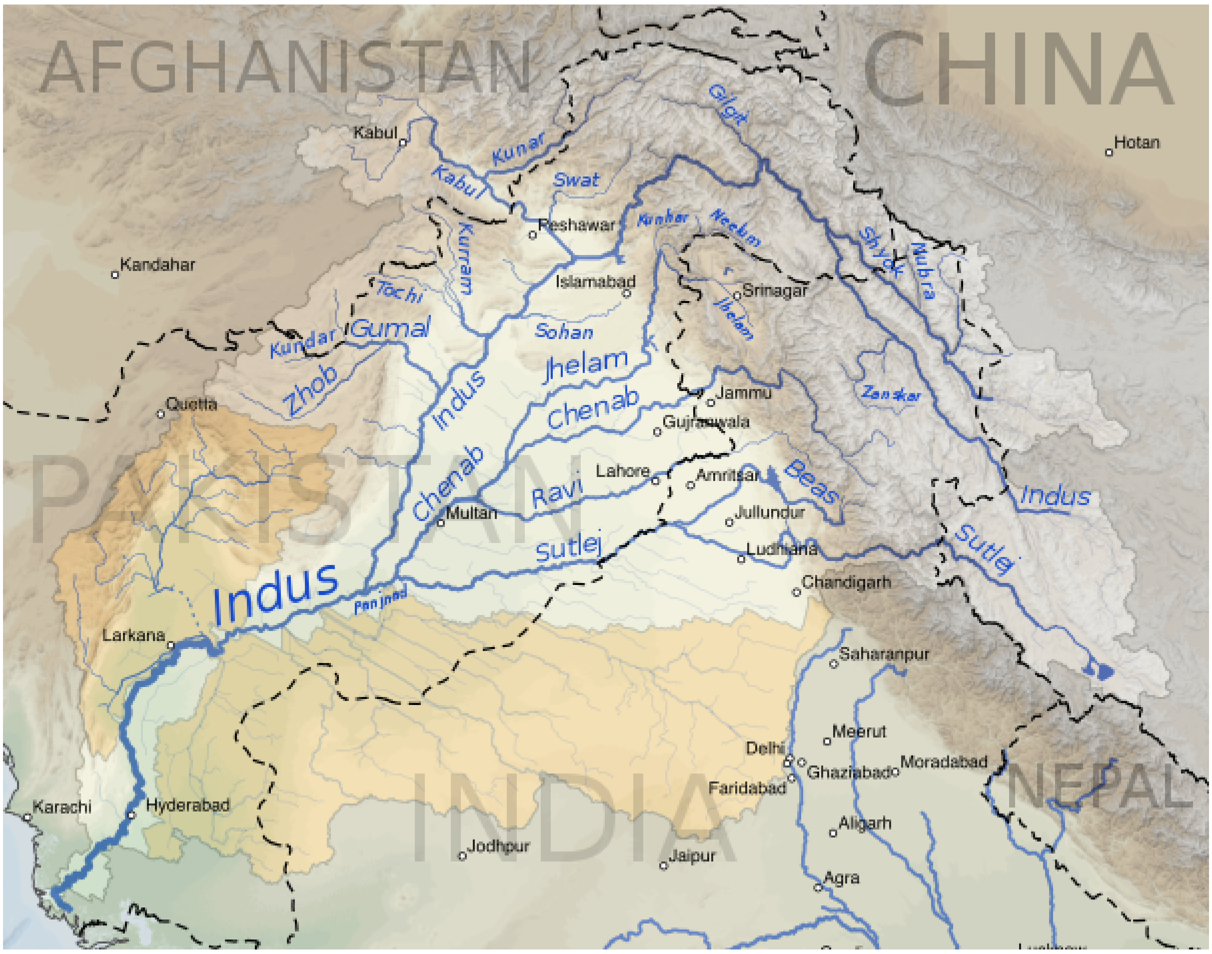
In High Mountain Asia, the glacial ice acts to protect against extreme water shortages on seasonal and longer timescales, because the glacial melt is sustained through droughts while all other stores of water in the basin decline[14]. Hydrological modelling predicts a decline in glacial meltwater contribution to the overall catchment hydrology by 2065 AD of -8% in the Indus, -18% in the Ganges and -20% in the Brahmaputra[1].



In southern China, just north of the border with Nepal, one unnamed Himalayan glacier flows from southwest to northeast, creeping down a valley to terminate in a glacial lake. At the end of the glacier's deeply crevassed snout sits a glacial lake, coated with ice in this wintertime picture. Just as nearby mountains cast shadows, the crevassed glacier casts small shadows onto the lake's icy surface. This glacial lake is bound by the glacier snout on one end, and a moraine—a mound formed by the accumulation of sediments and rocks moved by the glacier—on the other. Source: http://earthobservatory.nasa.gov/IOTD/view.php?id=43391&src=eoa-iotd

Glacier water resources in the Indus catchment

In the westerly Indus catchment, meltwater dominates water inputs during drought summers, and predicted glacier loss will add considerably to drought-related water stress[14]. The Indus and Aral basins are dominated by wet winters, dry summers, and have extensive glaciation[14]. The summer monsoon in these more westerly basins is also less dominant than that further east.



Map of the Indus River basin with tributaries labeled. Yellow regions are non-contributing parts of the watershed (e.g. the Thar Desert). From Wikimedia Commons (Keenan Pepper, https://commons.wikimedia.org/wiki/File:Indus_River_basin_map.svg)

In these basins, the highest proportion of glacial melt to overall basin hydrology occurs in the upper basins, closer to the glaciers. In the Indus basin, two thirds of the population (>120 million people) lives in the middle altitudes, where glacial meltwater is more significant. The use of water for hydropower and irrigation is concentrated at dams and barrages with average altitudes of 936-1484 m above sea level, in these middle altitudes[14]. In the Indus, 121 of 143 existing or planned dams are glacier-fed. In the upper Indus, without glaciers, summer monthly water flows would be reduced by 38%, and up to 58% in drought years. Water stress is likely to peak in the relatively dry summers in drought years as the glacier melt declines.

Video on glaciers as a water resource

Here is a video of Bethan Davies talking about glaciers as a water resource in Patagonia and the Himalaya.

Further reading

- 200 Million depend on melting glaciers for water
- Shrinking glaciers in Asia threaten water supply
- Warming climate is shrinking the Tuyuksu Glacier
- Redrawing the map of the World's international river basins
- River basins of the Himalaya
- What is the global volume of land ice and how is it changing?

- Glacier accumulation and ablation

References

1 Immerzeel WW, van Beek L P H & P, B. M. F. Climate change will affect the Asian water towers. *Science* **328**, 1382–1385 (2010).

2 Beniston, M. Climatic Change in Mountain Regions: A Review of Possible Impacts. *Climatic Change* **59**, 5-31, doi:10.1023/a:1024458411589 (2003).

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

4 Barnett, T. P., Adam, J. C. & Lettenmaier, D. P. Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature* **438**, 303, doi:10.1038/nature04141 (2005).

5 Bamber, J. L., Westaway, R. M., Marzeion, B. & Wouters, B. The land ice contribution to sea level during the satellite era. *Environmental Research Letters* (2018).

6 Zemp, M. *et al.* Historically unprecedented global glacier decline in the early 21st century. *Journal of Glaciology* **61**, 745-762, doi:10.3189/2015JoG15J017 (2015).

7 Zemp, M. *et al.* Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature*, 1 (2019).

8 Gardner, A. S. *et al.* A Reconciled Estimate of Glacier Contributions to Sea Level Rise: 2003 to 2009. *Science* **340**, 852-857, doi:10.1126/science.1234532 (2013).

9 Rowan, A. V. *et al.* The sustainability of water resources in High Mountain Asia in the context of recent and future glacier change. *Geological Society, London, Special Publications* **462**, 189-204 (2018).

10 Frans, C. *et al.* Implications of decadal to century scale glacio-hydrological change for water resources of the Hood River basin, OR, USA. *Hydrological processes* **30**, 4314-4329 (2016).

11 Immerzeel, W., Pellicciotti, F. & Bierkens, M. Rising river flows throughout the twenty-first century in two Himalayan glacierized watersheds. *Nature geoscience* **6**, 742 (2013).

12 Hejazi, M. I. *et al.* Integrated assessment of global water scarcity over the 21st century under multiple climate change mitigation policies. *Hydrology and Earth System Sciences* **18**, 2859-2883 (2014).

13 Bolch, T. *et al.* The state and fate of Himalayan Glaciers. *Science* **336**, 310-314 (2012).

14 Pritchard, H. D. Asia’s glaciers are a regionally important buffer against drought. *Nature* **545**, 169-174, doi:10.1038/nature22062 (2017).