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A call for an accurate presentation of glaciers as water resources

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Abstract

Glaciers are often portrayed as an important water resource in scientific research and public debate. However, the scientific literature calls for caution when presenting this idea. While melting glaciers can increase water insecurity, their contribution to runoff is often minor and other factors like excessive groundwater pumping for irrigation or surface and groundwater contamination pose much greater threats to water availability. As we consider the wide range of environmental impacts due to glacier changes, we must also question the “glacier as water resource” narrative that may unnecessarily contribute to public anxiety.

This article is categorized under:

Human Water > Water as Imagined and Represented
Science of Water > Water and Environmental Change

KEYWORDS

climate change, glacier, High Mountain Asia, water resource

1 | INTRODUCTION

The Cato institute, an influential American libertarian think tank, published a piece about glacier change in the High Mountain Asia (False Alarm over the Retreat of the Himalayan Glaciers, 2022) that was relayed in mainstream media (No, Himalayan Glaciers Melting Doesn't Mean Ganga Will Dry Up, 2022). Whereas the article is full of abject climate change denial, it raises a real issue about the contribution of glaciers to water resources. Based on the work of Armstrong et al. (2018), the authors concluded that glacier retreat in the High Mountain Asia does not threaten water supply in the highly populated regions of the Ganges, Indus, Brahmaputra basins. Indeed, the study of Armstrong et al. (2018) showed that annual meltwater produced on glacier areas is very low in comparison with rainfall runoff or snowmelt from non-glacierized areas in this region (Figure 1). By considering only melt from exposed glacier ice (which is a better measure of glacier contribution as argued below), the glacier contribution to annual runoff in the area of the Ganges and Brahmaputra basin above 2000 m asl is below 1%. These latter values are hydrologic inputs across elevations greater than 2000 m, which means that at lower elevation where most people live, it may be even less. The low contribution of glaciers to runoff in the upper Brahmaputra river basin was also evidenced by Prasch et al. (2013) who also estimated that icemelt represents 2% of the river flow at Lhasa city (3656 m asl).

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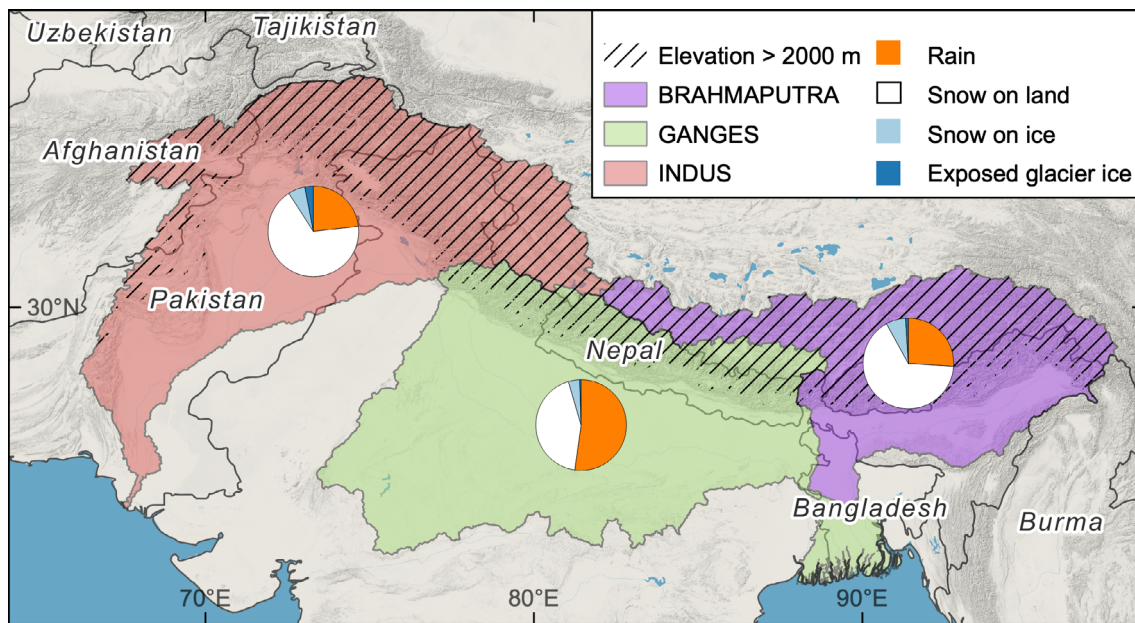


FIGURE 1 Respective contribution of rain, snow, snow on ice, and exposed glacier ice to runoff in three large Asian catchments above 2000 m altitude (from Armstrong et al., 2018). These results were obtained from remote sensing observations of snow and ice surfaces combined with hydrological modeling.

Glacier melt has a strong seasonal variability and therefore the contribution of icemelt to runoff can be higher at the monthly timestep, especially during the dry season, which is more relevant from a water resource perspective than an annual value. Still, the average icemelt contribution remains low at the monthly time step since it reaches at most 6% in the Indus over the period 2001–2014 (i.e., average contribution in September, Armstrong et al., 2018). Indeed, glacier melt does not necessarily occur during the dry season, in particular, snow and icemelt runoff increases during the monsoon due to the advection of warm air masses in the eastern Himalayas (Fugger et al., 2022; Laha et al., 2023).

The Armstrong et al. (2018) study shows however that melt from glacier ice is significant during the dry season in the Amu Darya basin (26% of runoff in September). The same conclusion was drawn by Pritchard (2019). The latter study is often cited to assert that glaciers provide large amounts of freshwater resources to billions of people in Asia (390 citations according to Web of Science on March 31, 2023 by counting both the retracted paper and its updated version (which corrected an error in the glacier mass balance calculation, see Pritchard, 2018)). In fact, the Pritchard (2019) study showed that glacier melt is less than 5% of the annual precipitation in all studied basins and acknowledged that it is not a significant input in the Ganges and Brahmaputra basins. This article focused on drought periods and presented glacier melt contribution as a fraction of runoff during the *driest month of the driest year* (“representative drought year”), that is, the year with the lowest annual precipitation for each basin in the 1951–2007 record (Pritchard, 2019). As a result, the monthly glacier melt contribution highlighted by Pritchard (2019, e.g., fig. 4) is the highest possible monthly value over a 57-year period. In addition, the glacier contribution (“net melt fraction”) was computed as the melt volume divided by the sum of the melt and net precipitation volumes during that month. Hence, as an extreme case, if there is no precipitation at all during this drought month, then the net melt fraction is 100%. Such concept of net melt fraction ignores the fact that baseflow during dry periods is also sustained by groundwater depletion, otherwise, the rivers of many non-glacierized catchments would run dry in summer. The groundwater contribution is difficult to assess since it depends on the geology of the catchments which is highly variable in a region as vast as the High Mountain Asia (Somers & McKenzie, 2020). Yet, Andermann et al. (2012) estimated that in Nepal, the groundwater storage has an approximate response time of 45 days and its capacity is larger than the annual snow and icemelt volume. As a consequence, the least we can say is that runoff sources during a dry month in Nepal are not limited to the surface water inputs like glacier melt and precipitation during that month.

In the light of these previous studies, some statements in the scientific literature such as “Glaciers in the Himalaya–Karakoram mountain ranges (...) modulate the flow of freshwater to almost 869 million people within the Indus, Tarim, Ganges and Brahmaputra river basins” (Nie et al., 2021) or “Glaciers are also a critical water resource for ~1.9 billion

people” (Rounce et al., 2023) appear greatly exaggerated. Then, how to blame the BBC journalist who wrote that “Billions of people around the world depend on the waters locked away in glaciers for their livelihoods, power and food” followed by the (accurate) statement “but climate change is melting them away” (Park, 2021)? The reader understands that, *because of glacier shrinkage*, billions of people are going to lack water in the near future, which is a strong and scary statement without scientific basis. Similar alarming statements come from international agencies or non-governmental organization. According to “Unesco glacier specialist,” “50% of humanity depends on glaciers as a source of water for domestic use, agriculture or hydroelectricity” (Barroux, 2022). Why such exaggerations?

2 | DEFINING THE CONTRIBUTION OF GLACIER TO WATER RESOURCE

First of all, there is a lack of consensus on what is the contribution of glaciers to water resources. Indeed, the very definition of the “glacier contribution” to water resources varies among the studies (Frenierre & Mark, 2014; Radić & Hock, 2014). Glacier contribution is generally defined as a ratio, the numerator being a measure of the glacier runoff and the denominator being a reference water flux. The denominator can be either the river discharge (Cui et al., 2023; Gascoïn et al., 2011; Huss, 2011; Huss & Hock, 2018), the precipitation (Kaser et al., 2010), or the net precipitation, that is, precipitation minus evaporation (Pritchard, 2019). The definition of the numerator, that is, the glacier runoff, also varies among the studies. Some authors consider that the glacier runoff is given by the melt of snow, firn, and ice over the glacier surface (Cui et al., 2023; Saks et al., 2022; Soruco et al., 2015), whereas others consider icemelt only (Azam et al., 2019; Burger et al., 2019; Prasch et al., 2013). Some authors include rain on the glacier area to estimate the glacier runoff (Huss, 2011; Huss & Hock, 2018). Others partition glacier runoff between seasonal melt (which includes snow and icemelt from the glacier ablation area) and net glacier mass loss (icemelt reducing the long-term glacier mass due to climate warming) (Bliss et al., 2014). Some authors estimate glacier runoff assuming the glaciers to be in equilibrium with the climate (Kaser et al., 2010), while others include the contribution of annual glacier mass loss to the total runoff (Huss & Hock, 2018; Pritchard, 2019).

The inconsistent definitions of glacier contribution to the water resources is likely to have caused confusion not only in the media but also in the scientific literature (López-Moreno et al., 2020). For example, Millan et al. (2022) refer to Soruco et al. (2015) to state that “the drainage basin of La Paz, with more than 2.2 M inhabitants, is strongly dependent on the water from ice melt that represents up to one-third of the water resources during the dry season”. In fact, Soruco et al. (2015) defined glacier runoff as the sum of the icemelt and snowmelt. Therefore, their water resources calculation includes the melt of the seasonal snow on the glaciers and the ice melt contribution was actually not estimated.

From a water resource perspective, it seems that annual glacier runoff (numerator) would be more adequately represented by the ice (and firn) melt, that is, the release of water that was stored multiple years by the glacier, that is, excluding the melt of the seasonal snowpack. In the case of a mountain glacier in balance with climate and neglecting mass loss by evaporation and sublimation, this meltwater flux is equal to the mass transported from the accumulation area to the ablation area every year. Miles et al. (2021) estimated this flux (referred to as balance ablation) for a large number of glaciers across High Mountain Asia based on remote sensing datasets of glacier velocity and elevation change. The balance ablation is the relevant measure of the sustainable contribution of a glacier to a catchment water balance. As illustrated in Figure 2, this contribution stands out in the Indus, Tarim, and Amu Darya among the major basins in High Mountain Asia. A closer analysis using a large sample of catchments shows that the glacier contribution (expressed as a flux per catchment unit area) decreases exponentially with the area of the glacierized catchment. The influence of glacier on streamflow is therefore expected to be significant in small headwater glacierized catchments.

Melt of the seasonal snowpack which accumulates and melt every year on a glacier surface should not be taken into account in glacier water resource assessment, unless it can be demonstrated that the magnitude of the snowfalls on a glacier is influenced by the presence of the glacier itself. Studies have shown that glaciers can be preferential snow accumulation areas but this was explained by the influence of the terrain topography on atmospheric conditions or avalanching and not by a positive feedback loop (Dadic et al., 2010; Gascoïn et al., 2013; Mott et al., 2019). In other words, according to the current knowledge, the same snowfall amount would be observed if the glacier was to be removed (Figure 3).

Regarding the denominator, it is not advisable to use river discharge measurements if the catchment of interest is large. This is because the flow along the course of a river is also influenced by output fluxes of natural and anthropogenic origins. In particular, river discharge from high alpine catchment contributes to groundwater recharge by stream infiltration (Müller et al., 2023) and is subject to withdrawals for irrigation or seasonal storage in reservoirs

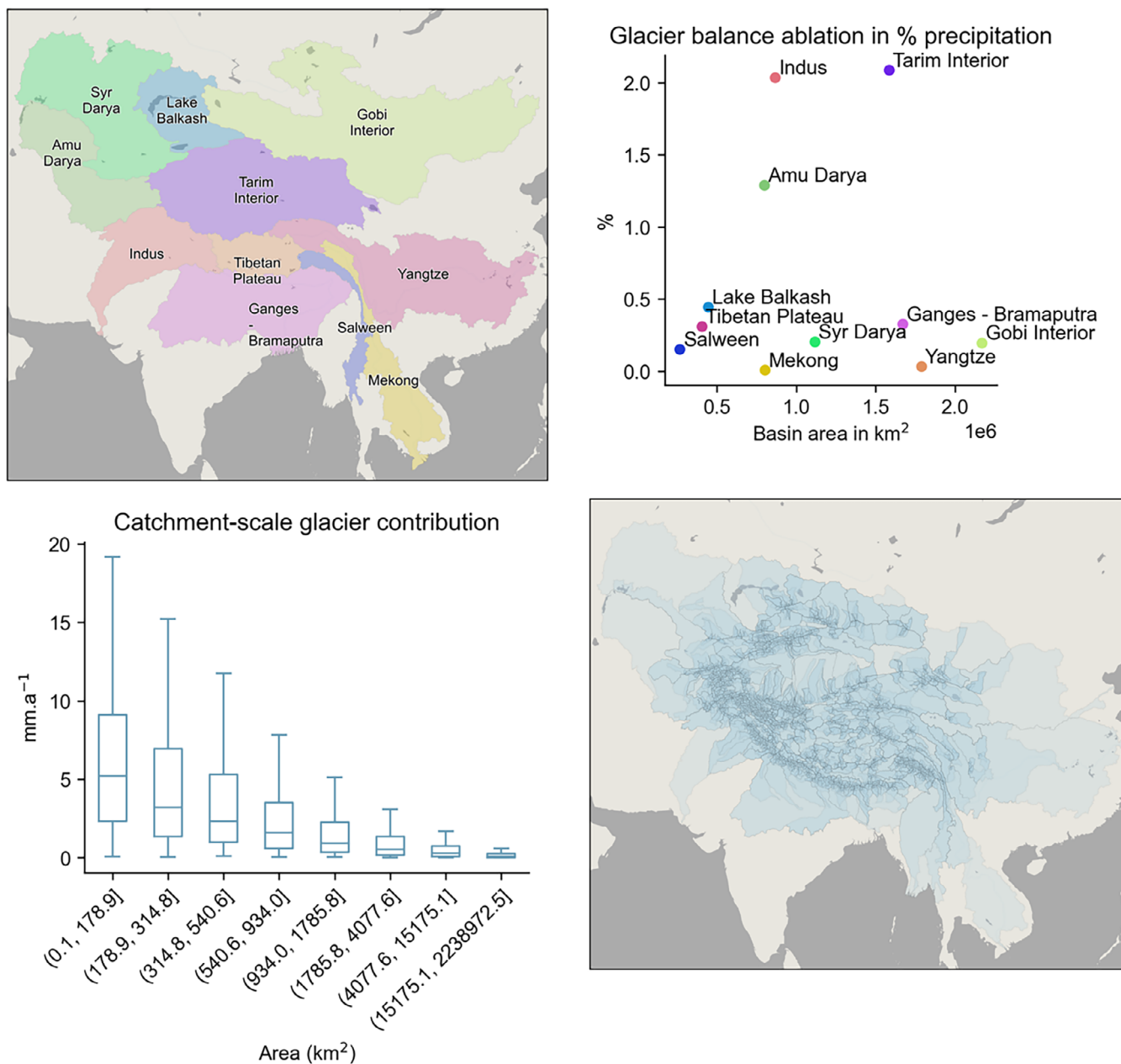


FIGURE 2 Balance ablation of glaciers larger than 2 km² in High Mountain Asia. The upper right panel shows the total water volume due to balance ablation in every major basin divided by the precipitation over the same period (2000–2016). The lower left panel shows the statistical distribution of the glacier contribution by catchment area. Here glacier contribution is expressed as the glacier balance ablation divided by catchment area for every glacierized catchment with Pfafstetter level 9–3 in the same region. Nonvalid values (32%) were imputed using a gradient boosting regression on glacier center longitude and latitude and accumulation area ratio ($R = 0.58$ on a 20% test sample). Glacier balance ablation can be seen as the ice ablation in the lower area of a glacier that is compensated by accumulation in the upper area over the same period (i.e., it does not include imbalance ablation due to climate change). Glacier data were sourced from Miles et al. (2021), precipitation from ERA5-Land and catchments polygons from HydroBASINS (Lehner & Grill, 2013).

(Wortmann et al., 2019). As a result, contribution from glaciers can be overestimated by default with increasing distance from the glaciers (Kaser et al., 2010). Estimating glacier contribution as the ratio of glacier runoff to river discharge implicitly assumes that glacier meltwater is never abstracted, confined to the river channel and reach the catchment outlet during the period of interest (typically a month). This can be a reasonable assumption in small and steep high mountain catchments, but it becomes difficult to justify in larger catchments, especially if the river runs through irrigated and populated areas (Figure 2). For example, Huss (2011) estimated that the contribution of glaciers

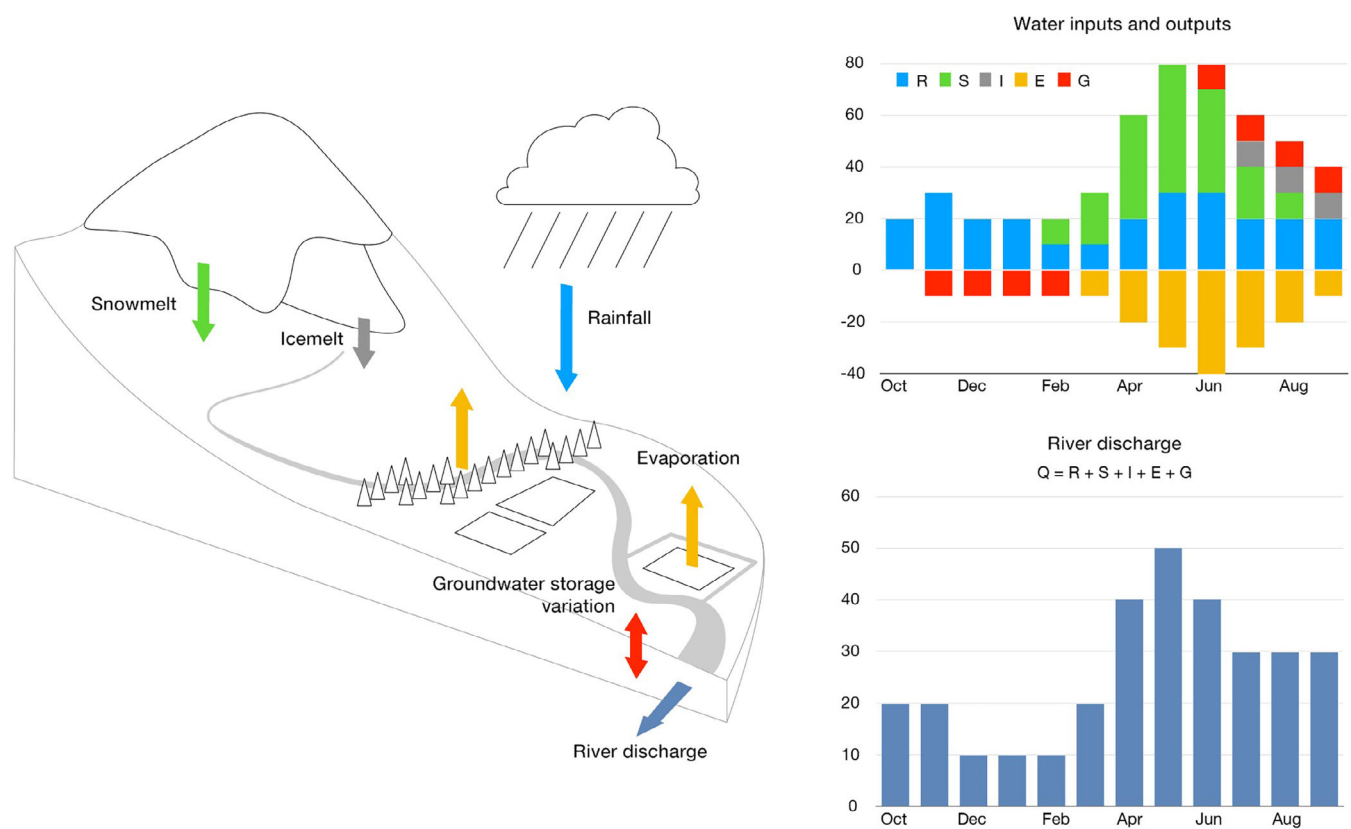


FIGURE 3 A schematic representation of the liquid water balance in a glacierized catchment. Liquid water inputs include snowmelt, icemelt, rainfall, whereas water losses occur through evaporation from natural and cultivated areas. Like glaciers, aquifers release water to the river during low flow periods. For the sake of simplicity, we have not represented lakes, wetlands, and reservoirs, which can be considered as seasonal storage similarly to the groundwater. The balance of water inputs and outputs illustrates why using the ratio of icemelt on river discharge as an indicator of “glacier contribution” can lead to inconsistencies. In this catchment, the glacier contribution in September would be 1/3 of discharge. Following the same calculation, groundwater and rainfall contribution would be 1/3 and 2/3, respectively, which is physically impossible (Figure 3).

to the Rhône river discharge near its outlet in the Mediterranean Sea reached 40% in August 2003, during the record-breaking heatwave. This value of 40% is often cited as the glacier contribution to the Rhone discharge but was computed including the melting of snow from the surface of the glaciers (arguably low in August) and ignored the numerous withdrawals in the Rhone river and its surrounding aquifer to irrigate crops and supply domestic water in this densely populated region of southeast France.

A proper quantification of the icemelt component in river discharge is actually a complex hydrological question. Weiler et al. (2018) clearly explained this issue and proposed an “effect tracking” method for this purpose. However, this approach remains difficult to implement and their recommendations are rarely considered even in the most recent studies dealing with this specific issue (Cui et al., 2023). The contribution of icemelt to river discharge can also be estimated using natural tracers, for example, by analyzing the composition of stable isotopes in water samples but this method requires heavy field work to collect water samples. This is possible in small catchments and has never been applied at the scale of entire mountain range (Chen et al., 2019). Numerical models could be used to compute the contribution of ice and snow melt in river and groundwater using single particle tracking but this approach is also not feasible at large scale due to its computing cost. In addition, particle tracking methods may not be relevant since they do not represent the propagation of pressures waves which drive the response of hydrologic systems to water input. In the meantime, we as scientists should communicate accurately on what exactly is considered as glacier contribution: does it include snowmelt? Which period of the year is considered? Is it a drought period? Which hydrological components are neglected (groundwater discharge, reservoir management...)?

3 | CONCLUSION

We should be careful when presenting the role of glaciers in water resource. As scientists, we have to provide accurate information about scientific research facts in public debate. Current knowledge does not suggest that billions of people will lack water *due to* glacier shrinkage in contrast to what is written in news articles, reports, and the introduction of many scientific articles. Other factors than glacier shrinkage are more likely to cause water scarcity in Asian countries like excessive groundwater pumping for crop irrigation (Rodell et al., 2009) or surface and groundwater contamination (Ahmed et al., 2006). This does not mean that glaciers are not important water resources. The key message is that glacier runoff can partly and temporarily compensate the lack of water resources during drought periods, especially in headwater catchments. Apart from the water resources perspective, there are other important motives to study glaciers like sea level rise (Gardner et al., 2013), biodiversity (Milner et al., 2017), hazard (Veh et al., 2020), and cultural value (Allison, 2015). In any case, the fragile beauty of glaciers should be a sufficient reason to study them before they vanish.

AUTHOR CONTRIBUTIONS

Simon Gascoin: Conceptualization (equal); writing – original draft (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

The author declares no conflicts of interest.

OPEN RESEARCH BADGES



This article has earned an Open Data badge for making publicly available the digitally-shareable data necessary to reproduce the reported results. The data is available at <https://github.com/sgascoin/balance-ablation>.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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REFERENCES

- Ahmed, M. F., Ahuja, S., Alauddin, M., Hug, S. J., Lloyd, J. R., Pfaff, A., Pichler, T., Saltikov, C., Stute, M., & van Geen, A. (2006). Ensuring safe drinking water in Bangladesh. *Science*, 314(5806), 1687–1688. <https://doi.org/10.1126/science.1133146>
- Allison, E. A. (2015). The spiritual significance of glaciers in an age of climate change. *WIREs Climate Change*, 6(5), 493–508. <https://doi.org/10.1002/wcc.354>
- Andermann, C., Longuevergne, L., Bonnet, S., Crave, A., Davy, P., & Gloaguen, R. (2012). Impact of transient groundwater storage on the discharge of Himalayan rivers. *Nature Geoscience*, 5(2), 127–132. <https://doi.org/10.1038/ngeo1356>
- Armstrong, R. L., Rittger, K., Brodzik, M. J., Racoviteanu, A., Barrett, A. P., Khalsa, S.-J. S., Raup, B., Hill, A. F., Khan, A. L., Wilson, A. M., Kayastha, R. B., Fetterer, F., & Armstrong, B. (2018). Runoff from glacier ice and seasonal snow in High Asia: Separating melt water sources in river flow. *Regional Environmental Change*, 19, 1249–1261. <https://doi.org/10.1007/s10113-018-1429-0>

- Azam, M. F., Wagnon, P., Vincent, C., Ramanathan, A. L., Kumar, N., Srivastava, S., Pottakkal, J. G., & Chevallier, P. (2019). Snow and ice melt contributions in a highly glacierized catchment of Chhota Shigri Glacier (India) over the last five decades. *Journal of Hydrology*, 574, 760–773. <https://doi.org/10.1016/j.jhydrol.2019.04.075>
- Barroux, R. (2022, November 3). Un tiers des glaciers du Patrimoine mondial de l'humanité aura disparu en 2050. *Le Monde.fr*. https://www.lemonde.fr/planete/article/2022/11/03/un-tiers-des-glaciers-du-patrimoine-mondial-de-l-humanite-aura-disparu-en-2050_6148274_3244.html
- Bliss, A., Hock, R., & Radić, V. (2014). Global response of glacier runoff to twenty-first century climate change. *Journal of Geophysical Research: Earth Surface*, 119(4), 717–730. <https://doi.org/10.1002/2013JF002931>
- Burger, F., Ayala, A., Farias, D., Shaw, T. E., MacDonell, S., Brock, B., McPhee, J., & Pellicciotti, F. (2019). Interannual variability in glacier contribution to runoff from a high-elevation Andean catchment: Understanding the role of debris cover in glacier hydrology. *Hydrological Processes*, 33(2), 214–229. <https://doi.org/10.1002/hyp.13354>
- Chen, H., Chen, Y., Li, W., & Li, Z. (2019). Quantifying the contributions of snow/glacier meltwater to river runoff in the Tianshan Mountains, Central Asia. *Global and Planetary Change*, 174, 47–57. <https://doi.org/10.1016/j.gloplacha.2019.01.002>
- Cui, T., Li, Y., Yang, L., Nan, Y., Li, K., Tudaji, M., Hu, H., Long, D., Shahid, M., Mubeen, A., He, Z., Yong, B., Lu, H., Li, C., Ni, G., Hu, C., & Tian, F. (2023). Non-monotonic changes in Asian Water Towers' streamflow at increasing warming levels. *Nature Communications*, 14(1), 1176. <https://doi.org/10.1038/s41467-023-36804-6>
- Dadic, R., Mott, R., Lehning, M., & Burlando, P. (2010). Wind influence on snow depth distribution and accumulation over glaciers. *Journal of Geophysical Research: Earth Surface*, 115, F01012. <https://doi.org/10.1029/2009JF001261>
- False Alarm over the Retreat of the Himalayan Glaciers. (2022, May 3). Cato Institute. <https://www.cato.org/policy-analysis/false-alarm-over-retreat-himalayan-glaciers>
- Frenierre, J. L., & Mark, B. G. (2014). A review of methods for estimating the contribution of glacial meltwater to total watershed discharge. *Progress in Physical Geography: Earth and Environment*, 38(2), 173–200. <https://doi.org/10.1177/0309133313516161>
- Fugger, S., Fyffe, C. L., Fatichi, S., Miles, E., McCarthy, M., Shaw, T. E., Ding, B., Yang, W., Wagnon, P., Immerzeel, W., Liu, Q., & Pellicciotti, F. (2022). Understanding monsoon controls on the energy and mass balance of glaciers in the Central and Eastern Himalaya. *The Cryosphere*, 16(5), 1631–1652. <https://doi.org/10.5194/tc-16-1631-2022>
- Gardner, A. S., Moholdt, G., Cogley, J. G., Wouters, B., Arendt, A. A., Wahr, J., Berthier, E., Hock, R., Pfeffer, W. T., Kaser, G., Ligtenberg, S. R. M., Bolch, T., Sharp, M. J., Hagen, J. O., van den Broeke, M. R., & Paul, F. (2013). A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. *Science*, 340(6134), 852–857. <https://doi.org/10.1126/science.1234532>
- Gascoin, S., Kinnard, C., Ponce, R., Lhermitte, S., MacDonell, S., & Rabatel, A. (2011). Glacier contribution to streamflow in two headwaters of the Huasco River, dry Andes of Chile. *Cryosphere*, 5(4), 1099–1113. <https://doi.org/10.5194/tc-5-1099-2011>
- Gascoin, S., Lhermitte, S., Kinnard, C., Bortels, K., & Liston, G. E. (2013). Wind effects on snow cover in Pascua-Lama, Dry Andes of Chile. *Advances in Water Resources*, 55, 25–39. <https://doi.org/10.1016/j.advwatres.2012.11.013>
- Huss, M. (2011). Present and future contribution of glacier storage change to runoff from macroscale drainage basins in Europe. *Water Resources Research*, 47(7), W07511. <https://doi.org/10.1029/2010WR010299>
- Huss, M., & Hock, R. (2018). Global-scale hydrological response to future glacier mass loss. *Nature Climate Change*, 8(2), 135–140. <https://doi.org/10.1038/s41558-017-0049-x>
- Kaser, G., Großhauser, M., & Marzeion, B. (2010). Contribution potential of glaciers to water availability in different climate regimes. *Proceedings of the National Academy of Sciences*, 107(47), 20223–20227. <https://doi.org/10.1073/pnas.1008162107>
- Laha, S., Banerjee, A., Singh, A., Sharma, P., & Thamban, M. (2023). Climate sensitivity of the summer runoff of two glacierised Himalayan catchments with contrasting climate. *Hydrology and Earth System Sciences*, 27(2), 627–645. <https://doi.org/10.5194/hess-27-627-2023>
- Lehner, B., & Grill, G. (2013). Global river hydrography and network routing: Baseline data and new approaches to study the world's large river systems. *Hydrological Processes*, 27(15), 2171–2186. <https://doi.org/10.1002/hyp.9740>
- López-Moreno, J. I., García-Ruiz, J. M., Vicente-Serrano, S. M., Alonso-González, E., Revuelto-Benedí, J., Rico, I., Izagirre, E., & Beguería-Portugués, S. (2020). Critical discussion of: “A farewell to glaciers: Ecosystem services loss in the Spanish Pyrenees.”. *Journal of Environmental Management*, 275, 111247. <https://doi.org/10.1016/j.jenvman.2020.111247>
- Miles, E., McCarthy, M., Dehecq, A., Kneib, M., Fugger, S., & Pellicciotti, F. (2021). Health and sustainability of glaciers in High Mountain Asia. *Nature Communications*, 12(1), 2868. <https://doi.org/10.1038/s41467-021-23073-4>
- Millan, R., Mougnot, J., Rabatel, A., & Morlighem, M. (2022). Ice velocity and thickness of the world's glaciers. *Nature Geoscience*, 15(2), 2. <https://doi.org/10.1038/s41561-021-00885-z>
- Milner, A. M., Khamis, K., Battin, T. J., Brittain, J. E., Barrand, N. E., Füreder, L., Cauvy-Fraunié, S., Gislason, G. M., Jacobsen, D., Hannah, D. M., Hodson, A. J., Hood, E., Lencioni, V., Ólafsson, J. S., Robinson, C. T., Tranter, M., & Brown, L. E. (2017). Glacier shrinkage driving global changes in downstream systems. *Proceedings of the National Academy of Sciences*, 114(37), 9770–9778. <https://doi.org/10.1073/pnas.1619807114>
- Mott, R., Wolf, A., Kehl, M., Kunstmann, H., Warscher, M., & Grünewald, T. (2019). Avalanches and micrometeorology driving mass and energy balance of the lowest perennial ice field of the Alps: A case study. *The Cryosphere*, 13(4), 1247–1265. <https://doi.org/10.5194/tc-13-1247-2019>
- Müller, T., Roncoroni, M., Mancini, D., Lane, S. N., & Schaeffli, B. (2023). Current and future role of meltwater-groundwater dynamics in a proglacial Alpine outwash plain. *EGU sphere*, 1–34. <https://doi.org/10.5194/egusphere-2022-1503>

- Nie, Y., Pritchard, H. D., Liu, Q., Hennig, T., Wang, W., Wang, X., Liu, S., Nepal, S., Samyn, D., Hewitt, K., & Chen, X. (2021). Glacial change and hydrological implications in the Himalaya and Karakoram. *Nature Reviews Earth & Environment*, 2(2), 91–106. <https://doi.org/10.1038/s43017-020-00124-w>
- No, Himalayan Glaciers Melting Doesn't Mean Ganga Will Dry Up. (2022, May 4). NDTV.Com. <https://www.ndtv.com/india-news/no-himalayan-glaciers-melting-doesnt-mean-ganga-will-dry-up-2945083>
- Park, W. (2021, August 11). The multi-billion dollar giants that are melting away. BBC Future. <https://www.bbc.com/future/article/20210810-the-multi-billion-dollar-giants-that-are-melting-away>
- Prasch, M., Mauser, W., & Weber, M. (2013). Quantifying present and future glacier melt-water contribution to runoff in a central Himalayan river basin. *The Cryosphere*, 7(3), 889–904. <https://doi.org/10.5194/tc-7-889-2013>
- Pritchard, H. D. (2018). Retraction note: Asia's glaciers are a regionally important buffer against drought. *Nature*, 555, 274. <https://doi.org/10.1038/nature25779>
- Pritchard, H. D. (2019). Asia's shrinking glaciers protect large populations from drought stress. *Nature*, 569, 649–654. <https://doi.org/10.1038/s41586-019-1240-1>
- Radić, V., & Hock, R. (2014). Glaciers in the Earth's hydrological cycle: Assessments of glacier mass and runoff changes on global and regional scales. *Surveys in Geophysics*, 35(3), 813–837. <https://doi.org/10.1007/s10712-013-9262-y>
- Rodell, M., Velicogna, I., & Famiglietti, J. S. (2009). Satellite-based estimates of groundwater depletion in India. *Nature*, 460(7258), 999–1002. <https://doi.org/10.1038/nature08238>
- Rounce, D. R., Hock, R., Maussion, F., Hugonnet, R., Kochtitzky, W., Huss, M., Berthier, E., Brinkerhoff, D., Compagno, L., Copland, L., Farinotti, D., Menounos, B., & McNabb, R. W. (2023). Global glacier change in the 21st century: Every increase in temperature matters. *Science*, 379(6627), 78–83. <https://doi.org/10.1126/science.abo1324>
- Saks, T., Pohl, E., Machguth, H., Dehecq, A., Barandun, M., Kenzhebaev, R., Kalashnikova, O., & Hoelzle, M. (2022). Glacier runoff variation since 1981 in the Upper Naryn River Catchments, Central Tien Shan. *Frontiers in Environmental Science*, 9. <https://doi.org/10.3389/fenvs.2021.780466>
- Somers, L. D., & McKenzie, J. M. (2020). A review of groundwater in high mountain environments. *WIREs Water*, 7(6), e1475. <https://doi.org/10.1002/wat2.1475>
- Soruco, A., Vincent, C., Rabatel, A., Francou, B., Thibert, E., Sicart, J. E., & Condom, T. (2015). Contribution of glacier runoff to water resources of La Paz city, Bolivia (16° S). *Annals of Glaciology*, 56(70), 147–154. <https://doi.org/10.3189/2015AoG70A001>
- Veh, G., Korup, O., & Walz, A. (2020). Hazard from Himalayan glacier lake outburst floods. *Proceedings of the National Academy of Sciences*, 117(2), 907–912. <https://doi.org/10.1073/pnas.1914898117>
- Weiler, M., Seibert, J., & Stahl, K. (2018). Magic components—Why quantifying rain, snowmelt, and icemelt in river discharge is not easy. *Hydrological Processes*, 32(1), 160–166. <https://doi.org/10.1002/hyp.11361>
- Wortmann, M., Bolch, T., Su, B., & Krysanova, V. (2019). An efficient representation of glacier dynamics in a semi-distributed hydrological model to bridge glacier and river catchment scales. *Journal of Hydrology*, 573, 136–152. <https://doi.org/10.1016/j.jhydrol.2019.03.006>

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