Differential loss of glacier stored water in the Indus River basin†

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In this study, we assessed the glacier stored water (1,620 ± 340 Gt) using a combination of ice dynamics modelling and volume–area scaling method and estimated glacier mass loss (6.4%) from 2001 to 2013 for the Indus River basin. Results indicate that the impact of climate change is not uniform across the basin, especially the stark difference between the Western Himalayan region where the glaciers are losing mass at the rate of –0.56 ± 0.27 m.w.e. per annum and the Upper Indus where the loss is at –0.18 ± 0.11 m.w.e. per annum.

Keywords: Climate change, glacier stored water, improved accumulation area ratio, mass balance, river basin.

THE Indus River basin covers an area of approximately 1 million km^2 and supports a population (2015) of 268 million people[1]. Glaciers act as buffers by providing the crucial meltwater supply during summer especially in drought years[2]. The contribution of snow and glacier melt to the total annual discharge of the river is about 62%, highlighting the high level of dependency of the basin on snow and glaciers[3]. Significant spatial variability is observed in the glacier mass loss across the basin[4–10], with some regions showing positive or zero mass loss[11]. However, the entire basin as a unit is consistently losing mass. This spatial variability in glacier mass loss can be attributed to a complex amalgamation of climate, morphological and topographical factors[12–17]. Climate change projections for the region suggest that contribution from glacier melt water would peak in the middle of this century and then decline[18]. Additionally, water demand for the basin is projected to increase in the future[19]. This large-scale loss in glacier mass will alter the state of water security for high-altitude mountain communities and people living downstream in the plains, thereby highlighting the urgency to mitigate and adapt to the ongoing climate change.

Recent estimates on mass loss, using the geodetic method, for the Indus River basin are –0.13 ± 0.04 m.w.e. per annum (2000–18)[5], –0.126 ± 0.196 m.w.e. per annum (2000–08)[8], and –4 ± 2 Gt per annum (2000–16)[9]. The climatic factors that most impact the mass balance of glaciers are temperature and precipitation. For the combined average of Western Himalaya and Karakoram from 1991 to 2015, the total change observed in mean temperature was (+) 0.65°C. Also, there was an increase in rainfall and a decrease in snowfall[20]. Future projections suggest that even if global warming is kept to 1.5°C, warming in the Hindu Kush Himalaya (HKH) will be slightly higher, while a 4–25% increase in monsoon precipitation is expected in the long term[1]. The climatic factors only partly explain the observed variability in mass loss. In High Mountain Asia (HMA), morphological variables explain 8–48% (depending on the region) of the observed variation in glacier mass balance[15]. The morphological variables are the impact of slope of the glacier tongue, mean glacier elevation, percentage of supraglacial debris cover and avalanche contributing area. The lake-terminating glaciers have lost more mass than debris-covered and clean glaciers, while debris-covered glaciers have lost more mass than clean glaciers[10]. Recent work in the Upper Indus shows that glaciers with southern slopes lose more mass than those with any other orientation[4]. These factors are not exhaustive but are major drivers of an observed change in glacier mass balance for the Indus region.

Our objective was to assess the impact of temperature and precipitation in understanding the spatial variability of glacier mass loss in the Indus River basin using a recently developed IAAR (improved accumulation area ratio) mass balance model[21,22]. To the best of our knowledge, this model has not been previously applied to such a large geographical area. Further, the model is conveniently packed into a graphical user interface (GUI) allowing rapid reproducibility and easy modifications. We also aimed to develop a new volume area (VA) scaling equation whose scaling parameters represent our study region accurately. The results from this VA scaling equation must be used to interpret stored water at the basin scale and not for an individual glacier. The future projection for glacier mass loss uses a combination of the mass balance model and inversion of VA scaling equation[23] to estimate the future changes in glacier area[24,25]; therefore, the development of a region-specific VA scaling equation is crucial. Further efforts to integrate the impact of morphology, topography, and other climatic variables,

†The source code for the Python-based graphical user interface will be made available upon request.

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high-resolution gridded climate data and results from the global circulation model will be considered in future studies.

Study area

The Indus River basin has 28,116 glaciers spread over 26,736 ± 1,337 km^2 geographical area (Table 1). The number of glaciers and the glaciated area was estimated using a mixed inventory from glacier area mapping for discharge in Asian mountains (GAMDAM)[26] and Randolph glacier inventory (RGI)[27]. The estimated elevation range of the glaciers, using advanced spaceborne thermal emission and reflection radiometer (ASTER)-based global digital elevation model (GDEM) was 2250–8550 m amsl. To understand the spatio-temporal variability of glacier mass loss in the basin we divided the entire region into smaller sub-basins, viz. Sutlej, Beas, Ravi, Jhelum, Chenab and Indus (Figure 1). This division of the sub-basins will also extend the study in the future to understand the hydrological implications of glacier melt on the Indus water treaty[28]. Figure 1 shows the six meteorological stations spread over the Indus River basin from which the daily temperature and precipitation data were obtained. Table 1 shows the meteorological station datasets used by individual river basins when estimating their glacier mass balance. Supplementary Figure 1 shows the meteorological station data used by individual glaciers.

The Indus region receives more precipitation during the winter months from the western disturbance (WD)[29]. Annual precipitation substantially varies across the basin with a magnitude as low as 150 mm in the south to more than 2000 mm in the north[30,31]. The Upper Indus, Kabul and Jhelum receive most of their winter precipitation from WD, mostly in solid form[32,33]. Chenab and Sutlej are significantly influenced by the Indian Summer Monsoon (ISM) and WD[34], while Ravi and Beas are dominated by ISM[35].

Table 1. Summary of glaciated area, number of glaciers and meteorological station data used in the Indus River basin. The number of glaciers and glacier area were estimated using a mix of RGI and GAMDAM inventory (refer to text for further details)

Sub-basin	Glacier area (km^2)	No. of glaciers	Meteorological station
Upper Indus	19,246 ± 880	17,616	Siachen, Leh
Kabul	2138 ± 107	3087	Siachen
Jhelum	277 ± 13.8	1011	Pahalgam
Ravi	162 ± 8	303	Bhuntar
Beas	506 ± 25	560	Bhuntar
Chenab	2824 ± 141	2881	Pahalgam, Kaza
Sutlej	1583 ± 79	2658	Kaza, Rakcham

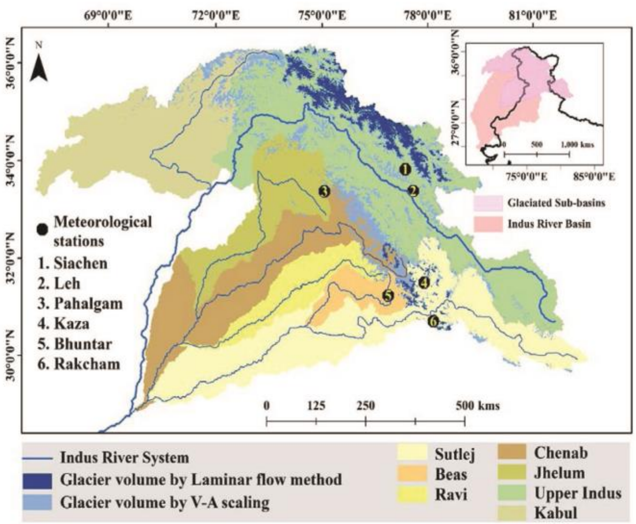

Figure 1. Map showing location of Indus River basin (inset), river network, glaciated area, sub-basins, and meteorological stations used in the analysis. The glaciers are highlighted in two colours to differentiate the choice of model in determining glacier volume. The entire basin has 28,116 glaciers (RGI and GAMDAM inventory) with estimated 26,736 ± 1,337 km^2 of glaciated area.

Research methodology

The research methodology includes details on glacier inventory (Supplementary Table 1 and Figure 2), meteorological station data (Supplementary Figure 3), glacier volume estimation (Supplementary Figure 4) and glacier mass balance (Supplementary Figure 5). The glacier inventory section entails the rationale for the choice of mixed inventory of RGI and GAMDAM. The glacier volume section describes how the glacier volume, based on the laminar flow method, was sourced from other works and the methodology they followed. It also describes how the VA scaling equation was developed in this study. The glacier mass balance section briefly outlines the IAAR algorithm (ref. Supplementary Figures 3 and 4 for python tool developed based on this algorithm), its limitations, and uncertainty calculations.

Results and discussion

Basin temperature and precipitation trends

In this study, we have used two meteorological parameters – temperature (Figure 2) and precipitation (Figure 3) to estimate snow melt and snow accumulation respectively. These parameters were first obtained from the meteorological stations and later extended to higher elevations using temperature lapse rate (Supplementary Tables 2 and 3) and precipitation gradient (Supplementary Table 2). The spatial distribution of these parameters was limited to an average value for any given elevation, which is sufficient to estimate basin mass balance with a high degree of confidence[21,22,24,25]. The available station data of 13 years were insufficient to comment on the general trend of temperature and precipitation in the region. Therefore, exhaustive literature covering a large timespan has been cited here[1,36].

Glacier stored water

Estimates of glacier volume based on the laminar flow method are available for 900 glaciers spread over the Indus, Ganga and Teesta basins. To develop the VA scaling equation, we selected 802 glaciers with an area of less than 20 km^2 (Figure 4). Incorporating glaciers with a higher area results in higher error as well as non-random distribution of errors, i.e. the scaling equation consistently overestimates volume for glaciers with greater area (Supplementary Figure 5). Our estimated total glacier stored water in the Indus River basin was 1620 ± 340 Gt. However, there was substantial spatial variability in the distribution in the basin (Figure 5 and Table 2). Around 99% of the glaciers in the Indus River basin store less than 1 Gt of water.

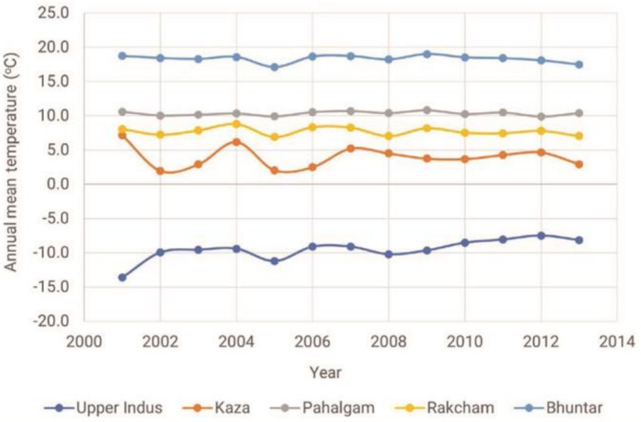

Figure 2. Annual mean temperature observed at different meteorological stations in the Indus River basin. Daily minimum and maximum temperatures were used to generate daily mean temperature, which was used to calculate the annual mean temperature. The Upper Indus was estimated by taking an average of Leh and Siachen meteorological station data.

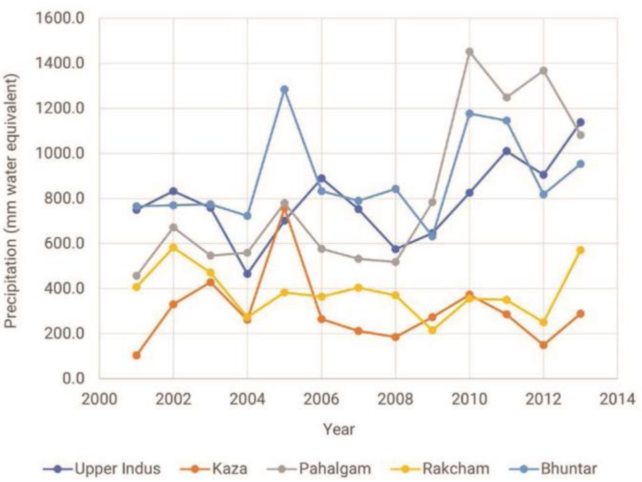

Figure 3. Total annual precipitation observed at different meteorological stations in the Indus River basin. All precipitation recorded in Bhuntar was rainfall in Leh 16% of the observed precipitation was rainfall, in Pahalgam 11% of the observed precipitation was snowfall and for others it was completely snowfall. The Upper Indus was estimated by taking the average of Leh and Siachen meteorological station data.

Frey *et al.*[37] have suggested that the total glacier volume in the Karakoram and Western Himalayas ranges from 2187 to 3531 km^3 depending on the method of estimation. They used six methods to estimate glacier volume, of which three methods used VA scaling. The scaling parameters employed in these equations were developed either using alpine glaciers[38], or theoretical relationship[39], or from thickness–area relation[40] of only 15 glaciers. These scaling parameters were not developed for the Himalayan region and therefore differed considerably from our estimates. Consequently, our estimated glacier stored water for the region was less than the previously published estimates.

Glacier mass balance

The mean glacier mass balance of the Indus River basin estimated from 2001 to 2013 using the IAAR mass balance model was –0.35 ± 0.13 m.w.e. per annum or –8.54 ± 3 Gt per annum. The cumulative mass loss for the entire period of 13 years was 111 ± 40 Gt. Comparison of glacier mass loss across the sub-basins showed substantial variation in rate (Figures 6 and 7). The equilibrium line altitude (ELA) for the Indus River basin did not vary much (Supplementary Figure 6) and its average value for 2001–13 was 5313 ± 135 m amsl. Researchers often study the Karakoram anomaly as well. However, the Indus River basin encompasses only that part of the Karakoram which falls within its boundary. Thereby, the present estimate of –0.15 ± 0.14 m.w.e. per annum is higher than other published studies (Table 3).

The spatial variation of the proposed model in the observed mass loss depends on altitude, hypsometry, precipitation and temperature. For any glacier to be in the state of

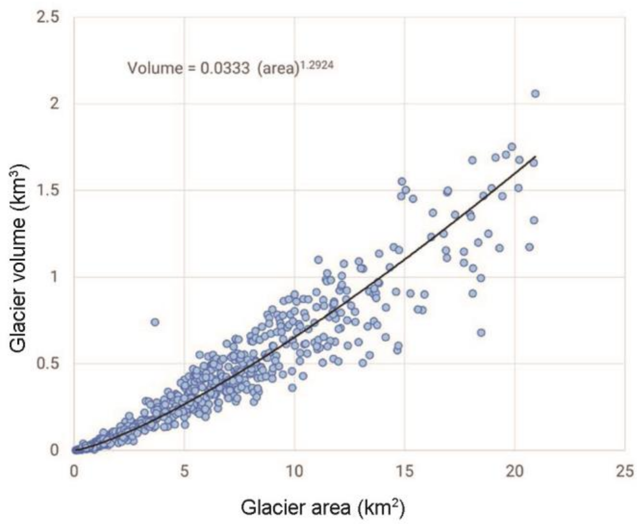

Figure 4. Volume–area scaling equation using glacier volume obtained from laminar flow method. The scaling equation was applied to 27,355 glaciers in the basin to determine their volume. The scaling parameters (eq. (3) in the Supplementary Information) estimated using 802 glaciers were $C_A = 0.0333$ and $\gamma = 1.2924$.

equilibrium or have zero mass balance, 66% of the glaciated area needs to be above ELA (Supplementary material, eq. (4)). Both temperature and precipitation will determine the position of basin-wide ELA and hypsometry will determine the mass balance of individual glaciers. Therefore, depending on the position of ELA in the basin and the glacier hypsometry, a slight change in ELA from year to year can affect the mass balance (Supplementary Figure 7).

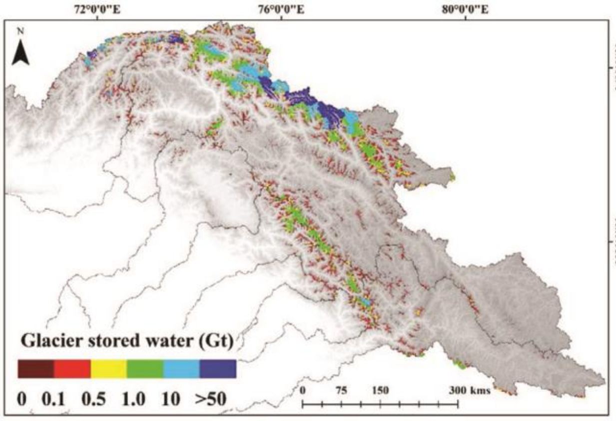

Figure 5. Spatial distribution of glacier stored water in the Indus River basin.

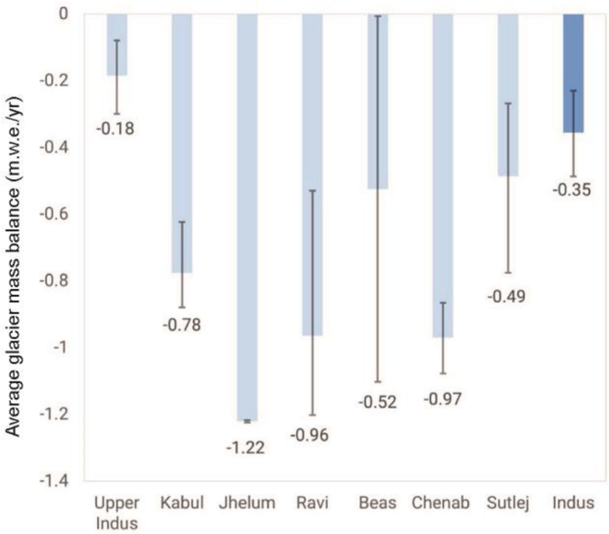

Figure 6. Comparison of annual glacier mass loss rate (2001–13) across various sub-basins of the Indus River basin.

Table 2. Glacier stored water in different sub-basins of the Indus River basin

Basin	Glacier stored water (Gt)
Upper Indus	1227 ± 258
Kabul	132 ± 28
Jhelum	8.3 ± 1.7
Chenab	159 ± 33
Ravi	5.7 ± 1
Beas	23 ± 5
Sutlej	66 ± 14

Refer to text for details on various methods used to estimate glacier stored water.

Table 3 compares our estimates of glacier mass loss with previously published studies for various regions. The estimates for the Western Himalayas and Upper Indus region were within the range of previously published studies. For the sub-region Karakoram, the eastern side showed positive mass balance while the western side showed near balanced to negative mass balance. Based on the nature of the proposed mass balance model, the difference in glacier hypsometry substantially affected this spatial variability in mass balance for the Karakoram (Figure 8). Groos *et al.*[41] modelled the surface mass balance of Karakoram glaciers using an enhanced degree-day model and found glacier mass loss at –0.92 m.w.e. for 2011. Although, the modelled value was relatively higher than our 2001–13 average of –0.15, the spatial variability agreed with our result; their study showed positive mass balance in the North and North East region and negative mass balance in the West[41].

Further, based on ERA5 single-level data from 2001 to 2013 (ref. 42), we found that the Western part of the Karakoram (13-yr average, 2001–13) had 67% more snowfall than the Eastern part and it was approximately (13-yr average, 2001–13) 2.9°C warmer on average than Eastern Karakoram (Supplementary Figures 8 and 9). This preliminary analysis and input from ERA5 data suggest that the combination of temperature, precipitation and glacier hypsometry increases glacier mass loss for Western Karakoram compared to Eastern Karakoram. Detailed analysis would require radiation balance, heat flux and morphological variables as input, which we plan to undertake as future work.

Conclusion

The Indus River basin is a transboundary region with multiple stakeholders – India, Pakistan, China and Afghanistan – being

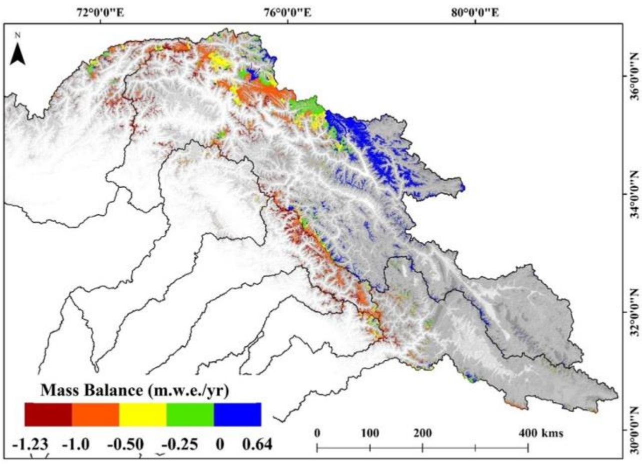

Figure 7. Spatial distribution of glacier mass balance in Indus River basin using IAAR glacier mass balance model from 2001 to 2013.

Table 3. Comparison of the present study with previous published values for glacier mass balance

Reference	Study region	Period	Mass balance (m.w.e per annum)
Present study	Indus River basin	2001–13	–0.35 ± 0.13
Present study	Upper Indus	2001–13	–0.18 ± 0.11
Present study	Western Himalaya	2001–13	–0.56 ± 0.27
Present study	Karakoram	2001–13	–0.15 ± 0.14
9	Indus River basin	2000–16	–0.16 ± 0.08
5	Indus River basin	2000–18	–0.13 ± 0.04
43	Indus River basin	1970 onwards	–0.21
4	Upper Indus	2000–12	–0.29 ± 0.29
25	Sutlej	1985–2013	–0.44 ± 0.46
24	Spiti	1985–2013	–0.56 ± 0.46
22	Chandra	1985–2013	–0.61 ± 0.46
44	Chandra	2013–19	–0.59 ± 0.12
45	Spiti Lahaul	1999–2011	–0.45 ± 0.13
46	Suru	1994–2018	–0.69 ± 0.28
47	Beas	1986–2000	–0.22
48	Karakoram	1975–2010	–0.01
49	Karakoram	1973–2000	–0.09 ± 0.03
14	Shyok	2000–14	–0.1 ± 0.07
9	Karakoram	2000–16	–0.03 ± 0.07
41	Karakoram	2011	–0.92
48	Himalaya	1962–2015	–0.37

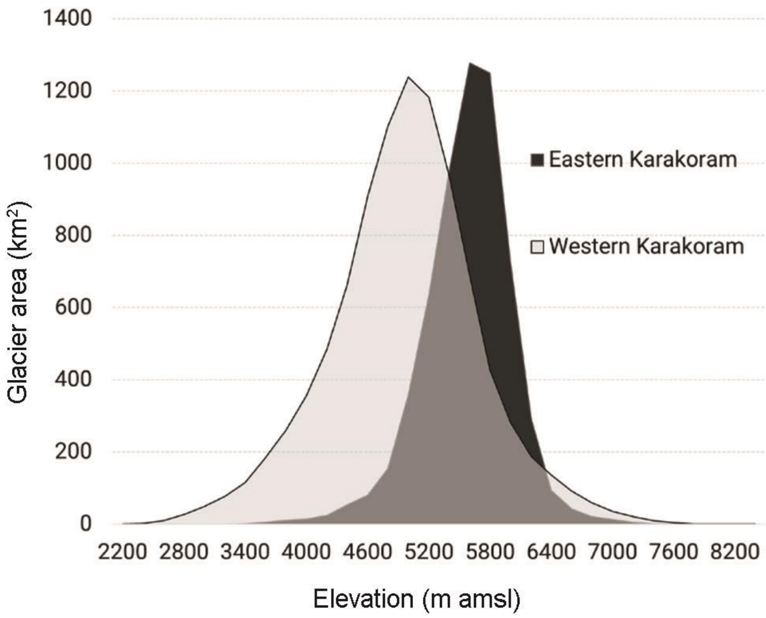

Figure 8. Glacier hypsometry for the Eastern and Western Karakoram. The glacier mass balance was assessed using Siachen meteorological data.

dependent for their water security. India and Pakistan also share an Indus water treaty (1960) for equitable distribution. The entire Indus region has diverse climatic, topographic and morphological conditions that affect the health of the glaciers. In this study, we have assessed total glacier stored water (1620 ± 340 Gt) in the region using a combination of the laminar flow model and VA scaling method, and glacier mass loss (2001–13, –0.35 ± 0.13 m.w.e. per annum) using the IAAR model. Results show significant spatial variability in stored water and mass loss, affecting the stakeholders differentially. Except for the Upper Indus basin, all other sub-basins show a substantial rate of glacier mass loss, which can affect future water availability, creating a need for relooking into some of the water-sharing practices in the basin. This is potentially because mass loss in the Upper Indus basin is low and glacier stored water is high, indicating longer sustainability of glacier melt water compared to other sub-basins in the Himalayas. This can cause new problems for water resources management in the basin. This analysis can be further extended by integrating regional climate models and climate reanalysis data. We aim to project into the future, the socio-economic impacts of glacier mass loss for all stakeholders as subsequent work.

Conflict of interest: The authors declare that there is no conflict of interest.

1. Wester, P., Mishra, A., Mukherji, A. and Shrestha, A. B., *The Hindu Kush Himalaya Assessment: Mountains, Climate Change, Sustainability and People*, Springer Nature, Switzerland, 2019, chapter 1, table 1.2, p. 5.
2. Pritchard, H. D., Asia's shrinking glaciers protect large populations from drought stress. *Nature*, 2019, **569**(7758), 649–654.
3. Mujumdar, P. P. and Tiwari, V. M., *Water Futures of India: Status of Science and Technology*, Indian National Science Academy, New Delhi, 2019.
4. Abdullah, T., Romshoo, S. A. and Rashid, I., The satellite observed glacier mass changes over the Upper Indus Basin during 2000–12. *Sci. Rep.*, 2020, **10**(1), 1–9.
5. Shean, D. E., Bhushan, S., Montesano, P., Rounce, D. R., Arendt, A. and Osmanoglu, B., A systematic, regional assessment of high mountain Asia glacier mass balance. *Front. Earth Sci.*, 2020, **7**, 363.
6. Hugonnet, R. *et al.*, Accelerated global glacier mass loss in the early twenty-first century. *Nature*, 2021, **592**(7856), 726–731.
7. Zemp, M. *et al.*, Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature*, 2019, **568**(7752), 382–386.
8. Muhammad, S., Tian, L. and Khan, A., Early twenty-first century glacier mass losses in the Indus Basin constrained by density assumptions. *J. Hydrol.*, 2019, **574**, 467–475.
9. Brun, F., Berthier, E., Wagnon, P., Kääb, A. and Treichler, D., A spatially resolved estimate of high mountain Asia glacier mass balances from 2000 to 2016. *Nature Geosci.*, 2017, **10**(9), 668–673.
10. Maurer, J. M., Schaefer, J. M., Rupper, S. and Corley, A., Acceleration of ice loss across the Himalayas over the past 40 years. *Sci. Adv.*, 2019, **5**(6), eaav7266.
11. Farinotti, D., Immerzeel, W. W., de Kok, R. J., Quincey, D. J. and Dehecq, A., Manifestations and mechanisms of the Karakoram glacier anomaly. *Nature Geosci.*, 2020, **13**(1), 8–16.
12. Kumar, P., Md Saharwardi, Banerjee, A., Mohd Azam, Dubey, A. K. and Murtugudde, R., Snowfall variability dictates glacier mass balance variability in Himalaya–Karakoram. *Sci. Rep.*, 2019, **9**(1), 1–9.
13. Wang, R., Liu, S., Shangguan, D., Radić, V. and Zhang, Y., Spatial heterogeneity in glacier mass-balance sensitivity across high mountain Asia. *Water*, 2019, **11**(4), 776.
14. Negi, H. S., Kumar, A., Kanda, N., Thakur, N. K. and Singh, K. K., Status of glaciers and climate change of East Karakoram in early twenty-first century. *Sci. Total Environ.*, 2021, **753**, 141914.
15. Brun, F., Wagnon, P., Berthier, E., Jomelli, V., Maharjan, S. B., Shrestha, F. and Kraaijenbrink, P. D. A., Heterogeneous influence of glacier morphology on the mass balance variability in High Mountain Asia. *J. Geophys. Res.: Earth Surf.*, 2019, **124**(6), 1331–1345.
16. Singh, G., Nela, B. R., Bandyopadhyay, D., Mohanty, S. and Kulkarni, A. V., Discovering anomalous dynamics and disintegrating behaviour in glaciers of Chandra-Bhaga sub-basins, part of Western Himalaya using DInSAR. *Remote Sensing Environ.*, 2020, **246**; https://doi.org/10.1016/j.rse.2020.111885.
17. Singh, G., Bandyopadhyay, D., Nela, B. R., Mohanty, S., Malik, R. and Kulkarni, A. V., Anomalous glacier thinning due to climate feedback mechanism in the Himalaya and evidences in other mountain ranges. *Remote Sensing Appl.: Soc. Environ.*, 2021, **22**; https://doi.org/10.1016/j.rsase.2021.100512.
18. Huss, M. and Hock, R., Global-scale hydrological response to future glacier mass loss. *Nature Climate Change*, 2018, **8**(2), 135–140.
19. Immerzeel, W. W. *et al.*, Importance and vulnerability of the world's water towers. *Nature*, 2020, **577**(7790), 364–369.
20. Negi, H. S., Kanda, N., Shekhar, M. S. and Ganju, A., Recent wintertime climatic variability over the North West Himalayan cryosphere. *Curr. Sci.*, 2018, **114**(4), 760–770.
21. Tawde, S. A., Kulkarni, A. V. and Bala, G., Estimation of glacier mass balance on a basin scale: an approach based on satellite-derived snowlines and a temperature index model. *Curr. Sci.*, 2016, **111**(12), 1977–1989.
22. Tawde, S. A., Kulkarni, A. V. and Bala, G., An estimate of glacier mass balance for the Chandra basin, Western Himalaya, for the period 1984–2012. *Ann. Glaciol.*, 2017, **58**(75pt2), 99–109.
23. Marzeion, B., Jarosch, A. H. and Hofer, M., Past and future sea-level change from the surface mass balance of glaciers. *Cryosphere*, 2012, **6**(6), 1295–1322.
24. Kulkarni, A., Prasad, V., Shirsat, T., Chaturvedi, R. K. and Bahuguna, I. M., Impact of climate change on the glaciers of Spiti River basin, Himachal Pradesh, India. *J. Indian Soc. Remote Sensing*, 2021, **49**(8), 1951–1963.
25. Prasad, V. *et al.*, Large losses in glacier area and water availability by the end of twenty-first century under high emission scenario, Satluj basin, Himalaya. *Curr. Sci.*, 2019, **116**(10), 1721–1730.
26. Nuimura, T. *et al.*, The GAMDAM glacier inventory: a quality-controlled inventory of Asian glaciers. *Cryosphere*, 2015, **9**(3), 849–864.
27. RGI Consortium, Randolph glacier inventory – a dataset of global glacier outlines, version 6. Technical report, National Snow and Ice Data Center, Boulder, Colorado, USA, 2017.
28. Indus water treaty. 1960; https://mea.gov.in/bilateral-documents.htm?dtl/6439/Indus (accessed on 26 September 2022).
29. Bolch, T. *et al.*, The state and fate of Himalayan glaciers. *Science*, 2012, **336**(6079), 310–314.
30. Archer, D. R. and Fowler, H. J., Spatial and temporal variations in precipitation in the Upper Indus basin, global teleconnections and hydrological implications. *Hydrol. Earth Sys. Sci.*, 2004, **8**(1), 47–61.
31. Dahri, Z. H., Ludwig, F., Moors, E., Ahmad, B., Khan, A. and Kabat, P., An appraisal of precipitation distribution in the high-altitude catchments of the Indus basin. *Sci. Total Environ.*, 2016, **548**, 289–306.
32. Hewitt, K., Glacier change, concentration, and elevation effects in the Karakoram Himalaya, Upper Indus basin. *Mt. Res. Dev.*, 2011, **31**(3), 188–200.
33. Shabeh ul Hasson, Pascale, S., Lucarini, V. and Böhner, J., Seasonal cycle of precipitation over major river basins in South and Southeast Asia: a review of the CMIP5 climate models data for present climate and future climate projections. *Atmos. Res.*, 2016, **180**, 42–63.
34. Bookhagen, B. and Burbank, D. W., Topography, relief, and TRMM-derived rainfall variations along the Himalaya. *Geophys. Res. Lett.*, 2006, **33**(8).
35. Pareta, K. and Pareta, U., Climate change impact on land and natural resource in Chamba tehsil of Himachal Pradesh State, India. *Int. J. Sci. Technol.*, 2014, **2**(4), 38.
36. Krishnan, R., Sanjay, J., Gnanaseelan, C., Mujumdar, M., Kulkarni, A. and Chakraborty, S., *Assessment of Climate Change over the Indian Region: A Report of the Ministry of Earth Sciences (MOES), Government of India*, Springer Nature, 2020.
37. Frey, H. *et al.*, Estimating the volume of glaciers in the Himalayan–Karakoram region using different methods. *Cryosphere*, 2014, **8**(6), 2313–2333.
38. Chen, J. and Ohmura, A., Estimation of alpine glacier water resources and their change since the 1870s. Hydrology in Mountainous Regions. I-Hydrological Measurements; the Water cycle. In Proceedings of Two Lausanne Symposia, IAHS Publ. No. 193, August 1990, pp. 127–135.
39. Bahr, D. B., Meier, M. F. and Peckham, S. D., The physical basis of glacier volume–area scaling. *J. Geophys. Res.: Solid Earth*, 1997, **102**(B9), 20355–20362.

40. Chaohai, L., Sharmal, C. K., Mayor-Mora, R., Xing, H., Sanbao, W. and Shengteng, Z., Report on first expedition to glaciers and glacier lakes in the Pumqu (Arun) and Poiqu (Bhote-Sun Kosi) River basins, Xizang (Tibet), China. Sino-Nepalese investigation of glacier lake outburst floods in the Himalayas. Technical report, Lanzhou Institute of Glaciology and Geocryology, China, Water and Energy Commission Authority, Nepal Electrical Authority, 1988.
41. Groos, A. R., Mayer, C., Smiraglia, C., Diolaiuti, G. and Lambrecht, A., A first attempt to model region-wide glacier surface mass balances in the Karakoram: findings and future challenges. *Geogr. Fis. e Din. Quat.*, 2017, **40**(2), 10.4461/GFDQ2017.40.10.
42. Hersbach, H. *et al.*, ERA5 hourly data on single levels from 1959 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS), 2018.
43. Bolch, T., Past and future glacier changes in the Indus River basin. *Indus River Basin*, Elsevier Inc., USA, 2019; https://doi.org/10.1016/B978-0-12-812782-7.00004-7.
44. Patel, A., Goswami, A., Dharpure, J. K., Meloth, T., Sharma, P., Kulkarni, A. V. and Oulkar, S., Estimation of mass and energy balance of glaciers using a distributed energy balance model over the Chandra River Basin (Western Himalaya). *Hydrol. Proc.*, 2021, **35**(2), e14058.
45. Gardelle, J., Berthier, E., Arnaud, Y. and Kääb, A., Region-wide glacier mass balances over the Pamir–Karakoram–Himalaya during 1999–2011. *Cryosphere*, 2013, **7**(4), 1263–1286.
46. Garg, S., Shukla, A., Garg, P. K., Yousuf, B., Shukla, U. K. and Lotus, S., Revisiting the 24 year (1994–2018) record of glacier mass budget in the Suru sub-basin, Western Himalaya: overall response and controlling factors. *Sci. Total Environ.*, 2021, **800**, 149533.
47. Li, L. *et al.*, Twenty-first-century glacio-hydrological changes in the Himalayan headwater Beas River basin. *Hydrol. Earth Syst. Sci.*, 2019, **23**(3), 1483–1503.
48. Azam, M. F., Wagnon, P., Berthier, E., Vincent, C., Fujita, K. and Kargel, J. S., Review of the status and mass changes of Himalayan–Karakoram glaciers. *J. Glaciol.*, 2018, **64**(243), 61–74.
49. Zhou, Y., Li, Z. and Li, J., Slight glacier mass loss in the karakoram region during the 1970s to 2000 revealed by KH-9 images and SRTM DEM. *J. Glaciol.*, 2017, **63**(238), 331–342.

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