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News & Views

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Mismatch between the population and meltwater changes creates opportunities and risks for global glacier-fed basins

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Mountain glaciers are indispensable suppliers of freshwater for human sustenance in extensive cold and arid areas of the world [1-3]. However, due to pronounced climate change over the last decades, the vast majority of the world's mountains have seen a rapid shrinking of glaciers with profound impacts on streamflow regimes of the mountains themselves, as well as downstream areas [4-6]. A wealth of studies have investigated the responses of glacier runoff to climate change and their impacts on streamflow at different scales, including single-glacier, glacierized mountain range, basin, regional, and even global scales [6-11]. These studies depicted a general picture that glacier runoff is expected to continue to rise for a certain period of time as climate changes and glaciers retreat, but after a maximum ("peak water"), the runoff will steadily decline [1,2,4-6]. These glacio-hydrological changes have important implications for human society in the basins and beyond, as climate-related glacio-hydrological changes strongly influence regional socio-economic development. As such, understanding and predicting these changes are pivotal to sustainability [12,13]. However, a global assessment of the consequences of the combined effects of glacier water resource (GWR) changes and population dynamics remains to be conducted. Integrating the recently available estimates of glacio-hydrological and population changes in an opportunity & risk framework, we aim at delivering a global assessment on the importance of GWR and the opportunities & risks associated with glacial meltwater changes and population dynamics.

The importance of GWR in terms of the supplying potential (SP) and downstream human dependence (demanding potential, DP) is first regionalized for all 193 glacier-fed basins on Earth (outside Antarctica). We assume that if the total glacier volume is large and ice coverage is high, then GWR has a high SP in this glacier-fed basin (Fig. S1 and Table S1 online). If the total population is large and the proportion of the highly water-stressed population (HWSP) is high, the DP ranks high, and *vice versa* (Fig. S2 and Table S1 online). The results show the important role played by GWR in the 36 glacier-fed basins, especially in the Indus, Ganges, Tarim, Junggar, Syr Darya and Amu Darya of Asia, Rapel, Mapocho and Santa of South America and Yukon of North America (Fig. 1 and Table S2 online). The total area of the 36 important glacier-fed basins (IGFBs) is 1.3×10^7 km^2, accounting for 9.7% of the world's total land area (outside Antarctica), in which all 109,447 glaciers cover a total area of 114,711 km^2. Approximately 1159.6 million people (15.8% of the world's total population) were living in these 36 IGFBs in 2015, of which approximately 87.3% (1012.3 million) were in Asia (Table S3 online). Moreover, nearly 12.6% (146.1 million) and 39.0% (461.8 million) were living under highly or extremely highly water-stressed conditions, with a water availability per capita of less than 500 m^3 a^{-1} and an average of more than 40% and 80% of the available supply withdrawn year-round, respectively. The vast majority of HWSP (95.9%) live in Asia (Table S3 online).

[INSERT FIGURE 1 HERE]

Huss et al. [5] presented a global-scale assessment of glacier runoff changes for 56 large-scale glacierized basins from 1980 to 2100, covering 22 IGFBs in this study. Following the threshold of absolute water scarcity (500 m^3 person per year) [12,14], we further qualify the population equivalent of glacier runoff for 22 IGFBs, representing the service potential of glacial meltwater (SPGM). The results indicate that the IGFBs with annual service potentials for an average year from 1980 to 2015 for more than 20 million people include the Brahmaputra (115.5 million), Indus (90.4 million), Ganges (77.51 million), Tarim (73.0 million), Aral Sea (53.8 million), and Yukon (29.3 million). Meltwater from glaciers supplies drainage runoff through accumulating snowfall during cold or/and humid periods and releasing it during hot or/and dry seasons, thus playing an important role seasonally [6]. As the insert of Fig. 2a shows, the seasonal SPGM can reach 2−3 times the annual SPGM in the majority of the investigated basins. In addition, the SPGM in an extreme (drought) year is much greater than that in an average year, both annually and seasonally (Fig. S3 online).

Among the 22 selected IGFBs, under the mid-range Representative Concentration Pathway (RCP) 4.5, the SPGM in 14 IGFBs will decline continually because the annual glacier runoff peak has already been reached before 2020 (Fig. 2a). Most of these IGFBs are in Europe, North and South America. The other 8 IGFBs would see the peak water during the 2030s−2050s. This applies to most IGFBs of Asia, such as the Indus, Tarim, Ganges, Brahmaputra, and Aral Sea (Syr Darya and Amu Darya), as well as the Yukon and Majes basins on other continents.

[INSERT FIGURE 2 HERE]

The human population living in the world's 36 IGFBs increased from 689.2 million in 1980 to 1164.4 million in 2015. The annual growth rate (AGR, 1.5%) was similar to the overall population increase rate across the globe during the same period. However, the AGRs of GFAs in Asia (1.7%) and South America (1.6%) were higher than that of the world's total population. The IGFAs population increased by only 6.6 million in Europe and 3.5 million in North America, respectively. At the basin scale, the increases of the populations in 6 IGFBs were greater than 10 million during 1980 to 2015, including those in the Ganges (208.0 million), Indus (141.6 million), Yangze (34.0 million), Brahmaputra (32.8 million), Amu Darya (13.2 million) and Amazonas (10.5 million). The AGR within IGFAs is the greatest in the Indus (2.3%), followed by the Amu Darya (2.1%), Brahmaputra and Amazonas (1.9%) (Fig. 2b).

The total population living in IGFBs would continue to increase until a maximum is reached under all shared socioeconomic pathway scenarios (SSPs) except SSP3, beyond which the population would gradually decline (Fig. S4 online). Specifically, the peak population will appear around 2060 and reach 1495.1 million under the intermediate pathway for mitigation and adaptation, i.e., SSP2. However, the peak population in the sustainable SSP1 will appear earlier (2050) and be lower by 161.3 million compared to that in SSP2. By the end of the 21st century, the GFAs population would decline to 993.4 million and 1364.4 million under SSP1 and SSP2, respectively (Fig. S5 online). At the basin scale, the population peak has already been reached before 2015 and the total population is expected to decline from 2015 in 4 IGFBs under SSP2, including the Ob, Indigirka, Danube and Qiangtang Plateau. However, compared to 2015, in most IGFBs of high mountains Asia and South America, the population would continue to increase rapidly until a maximum is reached between 2020 and 2060 (Fig. 2b), and a higher population is expected if the current trends are maintained (SSP2).

In general, both SPGM and population in IGFBs are expected to continue to rise for a certain period of time until a maximum is reached, beyond which they will gradually decline (RCPs, SSP1 and SSP2). However, there is a mismatch between the peak times of SPGM and population, which creates both opportunities and risks that vary with the basin and time. We further calculate the populations with consideration of seasonal opportunities (PO_i) and risks (PR_i) at the basin scale for each decade from the 1990s to the 2090s (with the 1980s as the first baseline period) in terms of SPGM changes and population dynamics. The opportunities and risks associated with only SPGM changes (POg_i and PRg_i) and jointly affected by SPGM and population changes ($POgp_i$ and $PRgp_i$) are also distinguished.

As shown in Fig. 2, although the SPGMs in the Indus, Ganges, Yangtze, Mekong, Rhine, Titicaca and Amazon basins have been increasing significantly before the "peak water" years, the opportunities associated with the increases of the SPGMs only meet the basic needs of part of the population due to the large population growth at the same time. However, in the other basins, the opportunities offered by the increase of the SPGM can not only seasonally meet the basic water needs for the increasing populations, but also relieve the water pressure for those populations under highly water-stressed conditions.

Most of the investigated basins would see the peak meltwater earlier than the projected peak population, not only creating a risk in terms of not meeting the basic water demands for the increased population but also imposing water pressure on the existing population. This is especially true for the Indus, Ganges, Amu Darya and Syr Darya. We found that both opportunities and risks are greatest in the Indus River basin, which provides a good example of typical consequences caused by mismatching between the meltwater and population changes. The increase in glacial meltwater can seasonally satisfy the basic needs of an additional 83.7 million people from the 1990s to the 2040s, but 129.1 million would be exposed to severe water scarcity due to the decrease in glacial meltwater and the population increase after the 2040s. After the peak population, the risk of water shortage would decline gradually.

Our study implies that resilience thinking, as well as more flexible and differential measures, should be taken by relevant stakeholders to seize the opportunities and mitigate the risks associated with different times and basins. When the SPGM initially increases, the utilization of GWR can improve regional human well-being through effective planning and engineering measures. Meanwhile, great attention should also be paid to effective adaptation once the SPGM continually declines after the population peak has been reached. Especially for international IGFBs in which substantial water resources are shared across borders, there are urgent needs for transboundary cooperation under a co-design and win-win strategy. Our study also implies that the transformation towards the sustainable pathway (SSP1) before 2030 can significantly reduce the risk of a water shortage caused by rapid population growth in the IGFAs of South and Central Asia, as well as South America.

This study assesses the combined effects of GWR changes and population dynamics globally. However, there still needs a high-resolution and fully coupled atmospheric–cryospheric–hydrological–socio-economic model in the future to reveal the complex interactions including trade-offs and synergies among the multiple components in each glacierized river basin due to the river discharge is also modified by precipitation, groundwater, evaporation and human activities such as agricultural irrigation and trans-regional water diversion, etc. [3]. In addition, more attention should be also paid to the extreme glacier runoff changes and the associated risks to build safe and sustainable communities over the world's high mountain areas and their surroundings.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Cunde Xiao, Deliang Chen and Bo Su designed and performed the study; Bo Su, Xue Ying, Yi Huang and Hongyu Zhao analysed the data; Bo Su, Rong Guo and Yanjun Che prepared the figures; Bo Su wrote the manuscript with the major contributions from Deliang Chen, Cunde Xiao and Aifang Chen. All authors contributed to the interpretation of findings, provided revisions to the manuscript, and approved the final manuscript.

Appendix A. Supplementary materials

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Fig. 1. Regionalization of the importance of the world's glacier water resources (GWR) in terms of their meltwater supplying potential (SP) and downstream human dependence (demanding potential, DP) in 2015 at the basin scale. The SP and DP are classified into extremely low (1), low (2), medium (3), high (4) and extremely high (5) categories based on normalized supply and demand indicators. The labels indicate 36 important glacier-fed basins (IGFBs) without low SP and DP values. The inset shows the basic information of IGFBs at the continental scale, including the glacierized basin number, population and proportion of the highly water-stressed population (HWSP) in 2015, glacier number, area and volume, and ice coverage.

Fig. 2. Changes in the service potential of glacial meltwater (SPGM) and population as well as their associated opportunities and risks in the world's IGFBs during historical (1980-2015) and future periods (2020-2100) under the mid-range Representative Concentration Pathway and Shared Socioeconomic Pathways, i.e., RCP4.5 and SSP2. (a) Annual and seasonal SPGM (insert, 4 months, from June to September in the Northern Hemisphere and from December to the next Marth in the Southern Hemisphere) in an average year during 1980 and 2015 and the annual glacier runoff peaks in 22 IGFBs. The labels show the 6 IGFBs with an annual SPGM of more than 20 million. (b) Population dynamics and their annual growth rates (AGR) during 1980 and 2015 (insert), along with future population peaks and their maximum change rates relative to 2015 in all 36 IGFBs. The labels indicate the 9 IGFBs with the biggest population change rates in the population peak year compared to 2015. Surrounding figures show seasonal opportunities and risks associated with only changes in the SPGM (POg_i and PRg_i) and jointly affected by changes in the SPGM and population dynamics ($POgp_i$ and $PRgp_i$) from the 1990s to the 2090s (with the 1980s as the first baseline period) in 21 IGFBs. The red labels show the HWSP with a water availability per capita of fewer than 500 m^3 a^{-1} in 2015.

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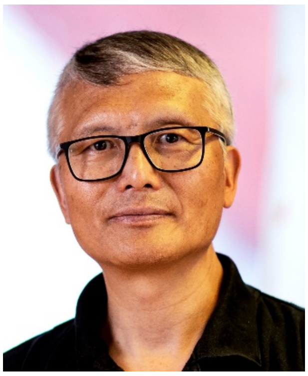

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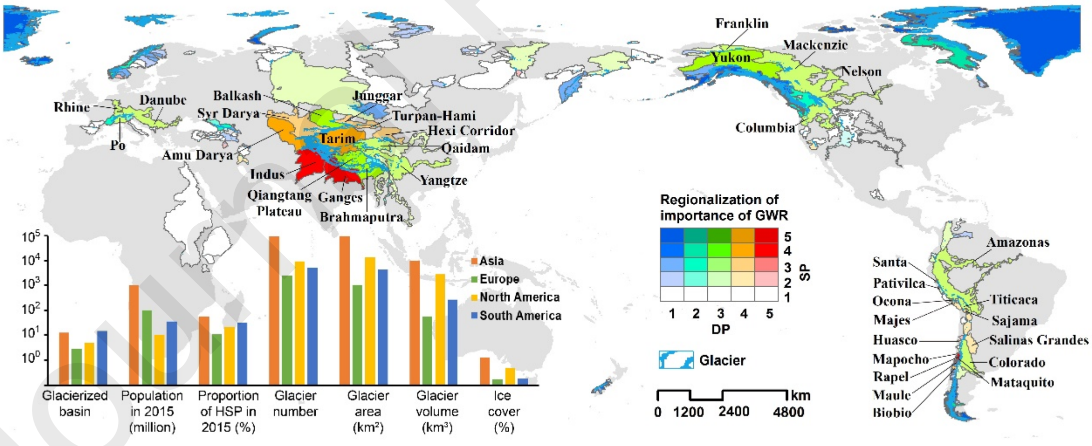

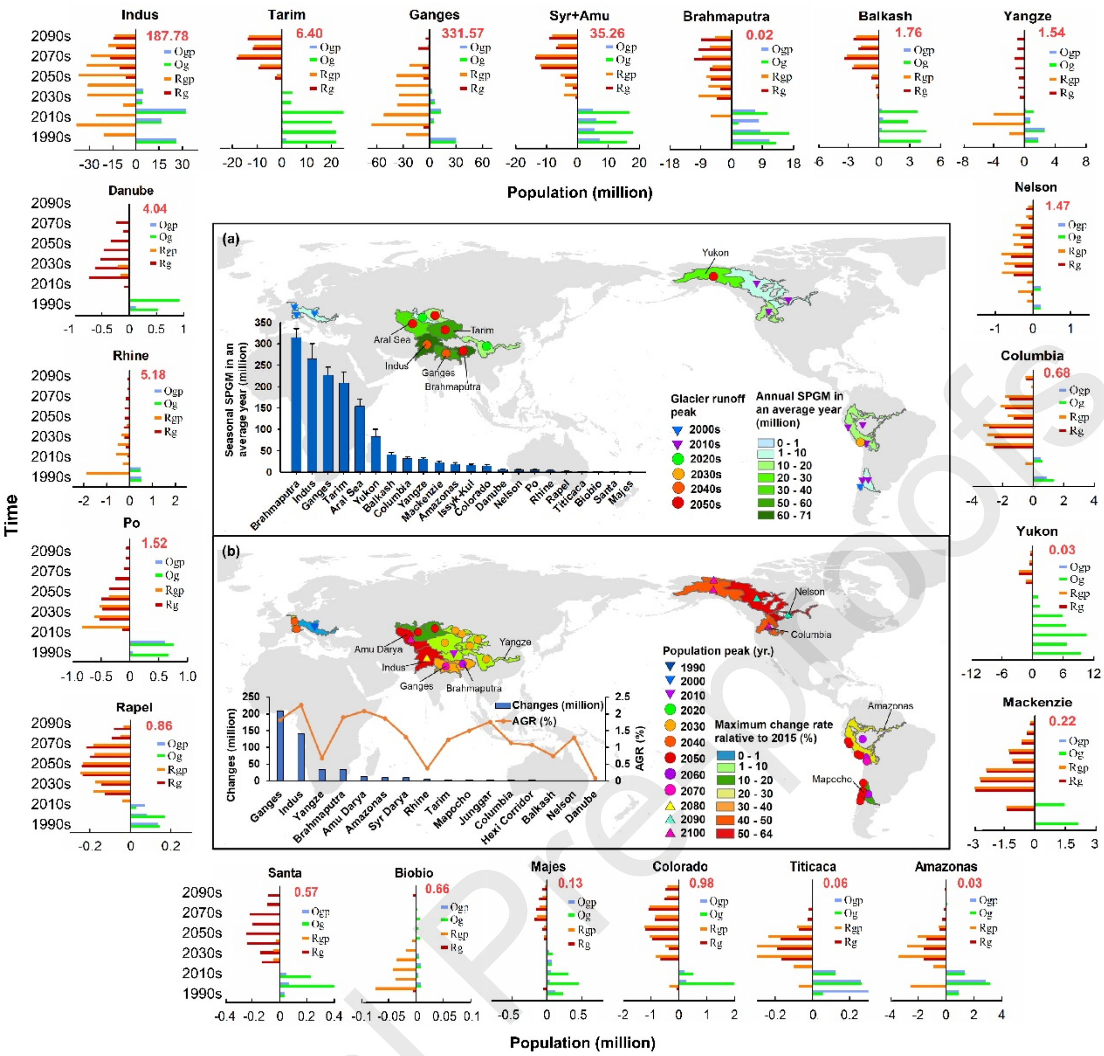

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