



Changes in the supply and demand potentials of China's glacier water resources in the 21st century: Spatiotemporal mismatches and combined effects

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Abstract

China's glacier water resources (GWRs) are not only indispensable suppliers of fresh water for humans living in large domestic areas but also affect the water supply to downstream neighbouring countries. Therefore, it is crucial to systematically evaluate the spatiotemporal (mis-) matches between the supply and demand potentials of China's GWRs and the combined supply and demand effects in the 21st century to enable regional sustainable development. To facilitate such research, in this study, we first regionalized the importance of China's GWRs in terms of the supply potential and downstream human dependence to reveal the spatial (mis-) matches between supply and demand potentials. Then, changes in the service potential of glacier meltwater and in population dynamics, as well as their temporal (mis-) matches and associated opportunities and risks, were further assessed at the river basin scale. The results showed that GWR plays an important role in 4 of 16 macroscale glacier-fed basins (i.e., Tarim, Junggar, Ili, and Zangxi) and 11 of 37 subbasins within the China region due to higher supply potential and demand potential in those basins. The importance of China's GWRs increases dramatically when taking the demand potential of downstream countries into account, especially in the Ganges and Indus river basins. The peaks in meltwater runoff from the most glacierized basins of the eastern Tianshan Mountains, eastern Qilian Mountains, and southeastern Tibetan Plateau of China occur slightly earlier than the projected peak population (around 2030) under the mid-range Shared Socioeconomic Pathway (SSP245), leading to a compound risk in terms of decreasing meltwater supply and increasing human dependence at the end of the 2020s. However, the peak meltwater is expected to occur later than the peak population in the Tarim, Qiangtang Plateau, and Qaidam basins. The opportunities offered by the increase in meltwater can relieve the water resource pressure for those populations under water-stressed conditions. Greater attention should also be paid to water shortage risks in the transboundary river basins, especially in the Indus and Ganges basins, because the peak meltwater within China is generally expected to occur sooner than the projected peak population of downstream countries. This study provides an effective planning and decision-making basis for the full utilization of China's GWRs and adaptation when glacier runoff declines.

Keywords: Glacier water resources; Population growth; China, Opportunity & risk; Climate change

1. Introduction

Human socioeconomic development depends strongly on glacier water resources (GWRs) in the extensive cold and arid regions of the world (Immerzeel et al., 2020; Su et al., 2022a;

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Miles et al., 2021; Yao et al., 2022). However, climate change has caused significant global-scale glacier mass loss and changes in drainage runoff and water availability (Immerzeel et al., 2010; Sorg et al., 2012; IPCC, 2021). Glacier runoff is expected to increase for a certain period, but after the ‘peak meltwater’, the runoff will then continuously decrease on a decadal scale (Huss and Hock, 2018; IPCC, 2019). Meanwhile, socioeconomic development has dramatically increased water demand (Viviroli et al., 2020; Immerzeel et al., 2020; Huang et al., 2022). Therefore, it is essential to link climate-related glacio-hydrological changes to the associated social-economic transitions to ensure regional sustainability. Some scholars have advanced related studies in recent years; for example, Pritchard (2019) analysed the importance of Asia's glacier meltwater in protecting downstream populations from drought stress, Biemans et al. (2019) and Lutz et al. (2022) quantified the past and/or future contribution of glacier meltwater to agriculture in South Asia using a coupled cryosphere-hydrology-crop model, and Su et al. (2022a) estimated the combined effects of GWR changes and population dynamics at the global glacierized river basin scale.

China has the largest glacier storage within the world's middle- and low-latitude regions, with a total of approximately 48,571 glaciers counted in the 2000s–2010s (Liu et al., 2015; Guo et al., 2015). The glaciers in the high mountains of western China are an important component of Asia's water towers (Yao et al., 2022), which are not only indispensable suppliers of fresh water for humans living in large domestic areas but also affect the water supply to downstream neighbouring countries (Su et al., 2022b). Many studies have investigated the changes in China's glacier runoff over the past few decades via *in situ* observations, empirical methods, and model simulations at both the individual glacier and catchment scales (e.g., Ye et al., 2012; Gao et al., 2018; Chen et al., 2019). The results of these studies have shown that glacier runoff has generally increased in the past several decades (Gao et al., 2010) but will eventually decrease by the end of the 21st century. However, the predicted timing of peak meltwater varies greatly from basin to basin because the way in which river basin-scale glacier runoff evolves depends strongly on multiple factors, such as climate change and glacier morphology in each basin (Huss and Hock, 2018; Su et al., 2022b). Ding et al. (2020) reviewed the literature and identified three scenarios for the future changes in China's river basin-scale glacier runoff: a) glacier runoff will continuously decrease in the future, such as is expected in the Kuche, Shiyang, Heihe, Hutubi and Nu river basins; b) peak meltwater will occur in the near-term, such as is expected in the Urumqi, Yangze, and Shule river basins; and c) glacier runoff will steadily increase before the middle of the 21st century, such as is expected in the Manasi, Yarkant, Muzarte, and Aksu river basins. However, there are significant differences regarding the simulated and projected results due to the inconsistent selection of glacierized basin scales and different methodologies applied. A spatially explicit 21st century assessment of China's GWRs changes with a coherent methodology and spatial scale remains to be

conducted in a systematic manner to clarify the service potential of GWRs for human society.

The changes in China's glaciers and the associated societal effects have also received increasing attention in recent years. Studies have assessed regional socioecological vulnerability to glacier change by constructing an indicator system (e.g., Yang et al., 2015) and have identified the social effects of glacier changes through questionnaire and interview methods (e.g., Zhu et al., 2008). However, there is still a lack of national assessment of the spatiotemporal (mis-) matches between the supply and demand potentials of China's GWRs and the combined supply and demand effects. This gap is addressed here by considering China's GWRs at spatially explicit and coherent river basin scales during the 21st century. Specifically, we first regionalized the importance of China's GWRs in terms of the supply potential (SP) and downstream human dependence (demand potential, DP) to reveal the spatial (mis-) matches between SP and DP. Then, changes in the service potential of glacier meltwater and in population dynamics within glacier-fed basins, as well as their temporal (mis-) matches, are assessed. On this basis, we further analysed the opportunities and risks associated with glacier meltwater changes and population dynamics. This study will provide an effective planning and decision-making foundation for the full utilization of China's GWRs and for adaptation when glacier runoff declines, as well as inform water resource management for transboundary river basins originating in China.

2. Materials and methods

2.1. Delineation of China's glacier-fed areas

Since mountain glaciers provide meltwater that is utilized by humans at the river basin scale, the basin is the scale adopted for delineating glacier-fed areas (Immerzeel et al., 2020; Su et al., 2022a). We first employed two types of data to identify China's glacier-fed basins, as follows: 1) The Randolph Glacier Inventory Version 6.0 (available from the National Snow and Ice Data Center at <https://nsidc.org/data/nsidc-0770/versions/6>), which contains all China's glacier outlines and glaciological parameters such as geographic location, area and elevation (RGI Consortium, 2017). 2) Hydrological basin boundaries of China and the surrounding countries, acquired from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (<http://www.resdc.cn>) and HydroBASINS (www.hydrosheds.org) (Lehner et al., 2008). We filtered intersecting data between the Chinese glacier inventory and the river basin classifications to obtain data on glacierized drainage basins in China and the associated downstream areas of neighbouring countries. Ultimately, China's glacier-fed areas were found to be distributed in 37 glacierized basins, which were further grouped into 16 macroscale drainage basins. Among them, six international macroscale basins originate from China's glaciers, i.e., the Ob (Irtysh River), Balkhash (Ili), Indus (Zangxi), Ganges, Brahmaputra (Yarlung Zangbo),

Irrawaddy, Mekong, and Salween (Su et al., 2022b). Then, for each glacierized river basin, we further eliminated the downstream subbasins that are not hydrologically connected to upstream glacierized drainage by following Immerzeel et al. (2020), thus ensuring that the glacier-fed areas included were directly connected with glacier meltwater runoff (Fig. 1).

2.2. Regionalization of the importance of China's glacier water resources

The importance of China's GWRs was regionalized according to the SP and DP at the glacierized basin scale. The SP is based on glacier volume (GV, km³) and ice coverage (IC, %). Herein, the ice coverage was calculated by the ratio of glacier area to basin area. We assumed that if the total glacier area is large and ice cover is high, then GWRs has a high SP in that glacierized basin. The DP is assessed based on the total human population and the proportion made up by the highly

water-stressed population (HWSP). If the total population is large and the HWSP is high, the DP is high. The global gridded population dataset was acquired from the History Database of the Global Environment (HYDE, <ftp://ftp.pbl.nl/hyde>), which was developed by the Netherlands Environmental Assessment Agency, to represent the population in the glacier-fed area (Klein et al., 2017). Baseline water stress was employed to analyse populations under different water stress levels in glacier-fed areas and was developed by the World Resources Institute (WRI) (Hofste et al., 2019). Baseline water stress measures the ratio of total water withdrawals (domestic, industrial, irrigation and livestock use, etc.) to available surface and groundwater supplies at annual, monthly and sub-basin scales. Baseline water stress is classified into five risk levels, i.e., low (<10%), low to medium (10%–20%), medium to high (20%–40%), high (40%–80%), and extremely high (>80%) (Gassert et al., 2013). Finally, the SP and DP are the average of their normalized indicators, which are further grouped into five classes: very low, low, medium, high, and

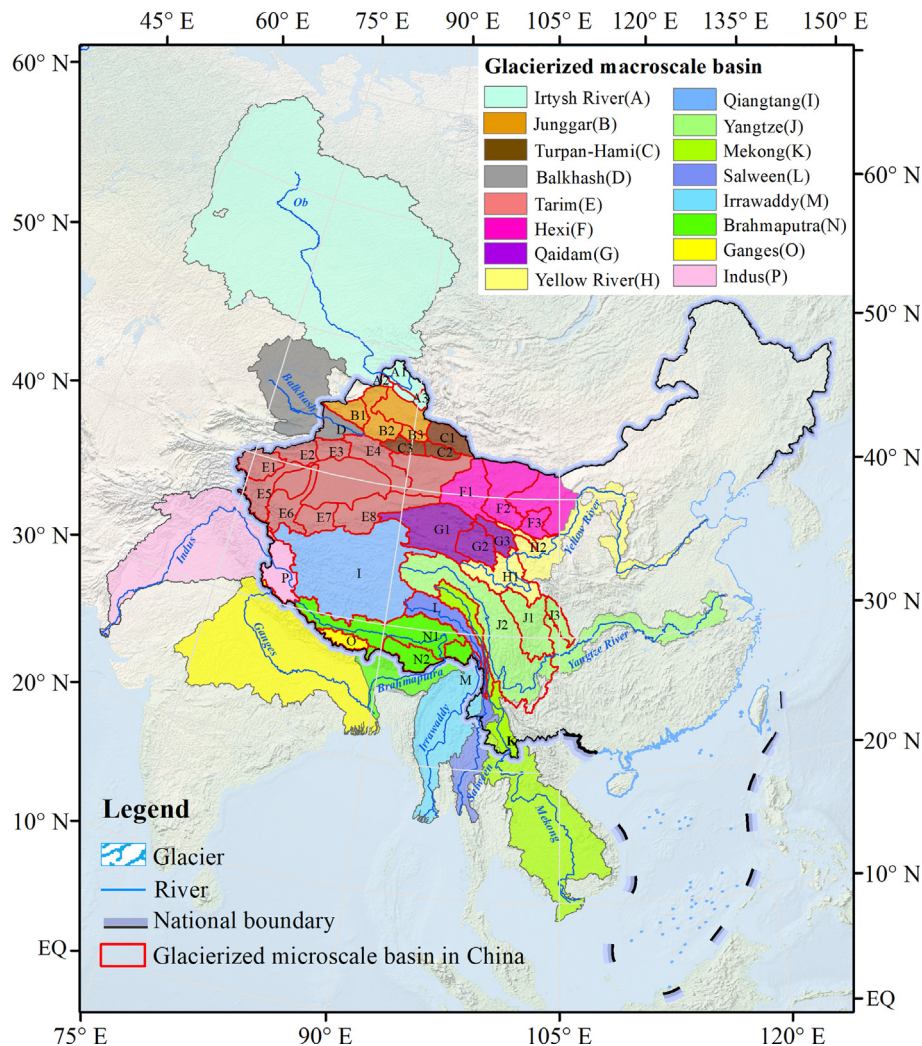


Fig. 1. Distribution of China's glacier-fed basins (The white labels indicate glacier-fed endorheic basins while the black labels show glacier-fed exoreic basins. The basin name corresponding to each basin ID can be found in Table A2).

very high (Table A1). The importance of GWRs is ranked high when SP and DP are both large across all glacierized areas.

2.3. Opportunities and risks associated with meltwater and population changes

The population levels with opportunities (P_{Oi}) and risks (P_{Ri}) in terms of glacier meltwater service potential (GMSP) and population growth were calculated at the decadal basin scale for the period from 2000 to 2100. The GMSP is defined as the population equivalent of glacier runoff (P_G) (Su et al., 2022a) by following the threshold of absolute water scarcity (500 m³ per capita per year) (Wada et al., 2011; Damkjaer et al., 2017). We also distinguished the opportunities and risks associated only with glacier meltwater changes (P_{Ogi} and P_{Rgi}) and those jointly affected by glacier meltwater changes and population growth (P_{Ogpi} and P_{Rgpi}).

To reveal the basin-scale glacier meltwater changes across China, we adopted the existing High Mountain Asia Glacier Projections that include monthly glacier mass and runoff changes in the 21st century. In this adopted dataset, glacier runoff was defined as the water that leaves the initially glacierized area (Huss and Hock, 2018). This dataset was created by the state-of-the-art regional glacier evolution model, i.e., the Open Global Glacier Model (OGGM), driven by monthly air temperature and precipitation data from ERA5-Land reanalysis for the historical simulations (2000–2021), and 10 bias-corrected general circulation models (GCMs) and six shared socioeconomic pathways (i.e., SSP119, SSP245, SSP370, SSP460, and SSP585) of the Coupled Model Inter-comparison Project Phase 6 (CMIP6) for the future projections (2022–2100) (Zhao et al., 2023). The model performance was also validated with glacier annual surface mass balance observations, and a two-stepwise method is employed to optimize the model parameters and select the optimal historical baseline climate dataset. To depict the basin-scale population change, the historical population count (1980–2015) and the future projections (2020–2100) under SSPs were used, with both having been obtained from the HYDE database and having a spatial resolution of 1 km (Goldewijk et al., 2017).

To assess the opportunities and risks associated with meltwater and population changes across various glacier-fed areas, first, decadal glacier runoff changes (ΔG_i) and the associated population equivalent (ΔP_{Gi}) were calculated using the threshold of absolute water scarcity over the period $i-1$ (the 2000s, 1990s, ..., 2080s) to i (2010s, 2000s, ..., 2090s). Then, the decadal population changes (ΔP_{Pj}) from $j-1$ (2000, 2010, ..., 2090) to j (2010, 2020, ..., 2100) were also calculated. Finally, P_{Ogi} , P_{Rgi} , P_{Ogpi} and P_{Rgpi} were assessed by applying the following principles proposed by Su et al. (2022a).

- (1) $P_{Ogi} = \Delta P_{Gi}$ if ΔG_i and $\Delta P_{Gi} > 0$; otherwise, $P_{Ogi} = 0$.
- (2) $P_{Ogpi} = \Delta P_{Gi}$ if $0 < \Delta P_{Gi} < P_{Pj}$, $P_{Ogpi} = \Delta P_{Opi}$ if $0 < P_{Pj} < \Delta P_{Gi}$; otherwise, $P_{Ogpi} = 0$.
- (3) $P_{Rgi} = \Delta P_{Gi}$ if ΔG_i and $\Delta P_{Gi} < 0$; otherwise, $P_{Rgi} = 0$.
- (4) $P_{Rgpi} = \Delta P_{Gi} - \Delta P_{Pj}$ if $\Delta P_{Gi} < 0$ and $\Delta P_{Gi} - \Delta P_{Pj} < 0$.

3. Results

3.1. Importance of China's glacier water resources

It was estimated that China's total glacier area was approximately 52×10^3 km² (Guo et al., 2015), accounting for 1.0% of the glacier-fed areas within China (5.1×10^6 km²). Approximately 248.3 million people (18.1% of China's total population) were living in China's glacier-fed areas in 2015, and nearly 14.8% (36.8 million) were living under high or extremely high water-stressed conditions with water availability per capita being less than 500 m³ per year. In these areas, on average, more than 40% of the available supply was withdrawn year round. Fig. 2a–b presents regionalized results showing the importance of GWRs within China based on SP and DP across the 37 microscale river basins and 16 macroscale basins. There are notable differences in glacier volume, ice coverage, total population and HWSP, representing in part the different SP and DP levels of GWRs within different glacierized river basin scales.

With respect to 14 glacierized macroscale river basins within China (Fig. 2a), the SP ranks highest in the Brahmaputra, followed by the Tarim, Ganges, and Qiangtang, due to their large glacier volumes and high ice cover. In contrast, SP is relatively low in seven macroscale river basins, including the Yellow, Mekong, Turpan–Hami, Irtysh, Hexi, Irrawaddy, and Yangze river basins, because of their smaller glacier volumes and lower ice cover. The DP is classified as high in four macroscale basins: Junggar, Ili, Tarim, and Hexi. Among the basin DPs, the DP in the Junggar basin ranked highest because of the large human population (6.1 million), of which 92.5% lived under high or extremely high water-stressed conditions in 2015. The Tarim River basin had the largest total population (9.5 million), but the HWSP was relatively low (64.6%). Since both SP and DP are high or extremely high, GWR plays an extremely important role in the Tarim River basin. GWR is also crucial in the Junggar, Ili, and Indus river basins within China, as these basins have medium SP but medium to high DP. GWR is not important in glacier-fed river basins with a higher SP but lower DP, lower SP but higher DP, or lower SP and DP.

Regarding the 37 glacierized microscale subbasins (Fig. 2b), the SP in seven subbasins ranks high or very high, as they mostly originate in the Himalaya Mountains, Kunlun Mountains, or Tianshan Mountains. However, SP is relatively low in more than half of the microscale basins, which mainly originate in the eastern Tibetan Plateau, Altai Mountains, or eastern Tianshan Mountains. Due to small populations or/and low HWSP, the DP in 14 of the microscale glacierized river basins was ranked as low; these basins are mainly distributed in the eastern and southern Tibetan Plateau and the Irtysh River basin. In contrast, the DP was ranked as high in most glacierized areas of the northern and eastern Tianshan Mountains and Tarim. Ultimately, (very) high SP and DP indicate that GWRs play an important role in the 11 microscale glacierized river basins, including the Junggar mid-branch and Aibi Lake basins, Keriya, Hotan, Haxgar, Qarqan, Aksu, Muzat, and Tarim Yarkant basin, as well as in the Zangxi and Ili river basins.

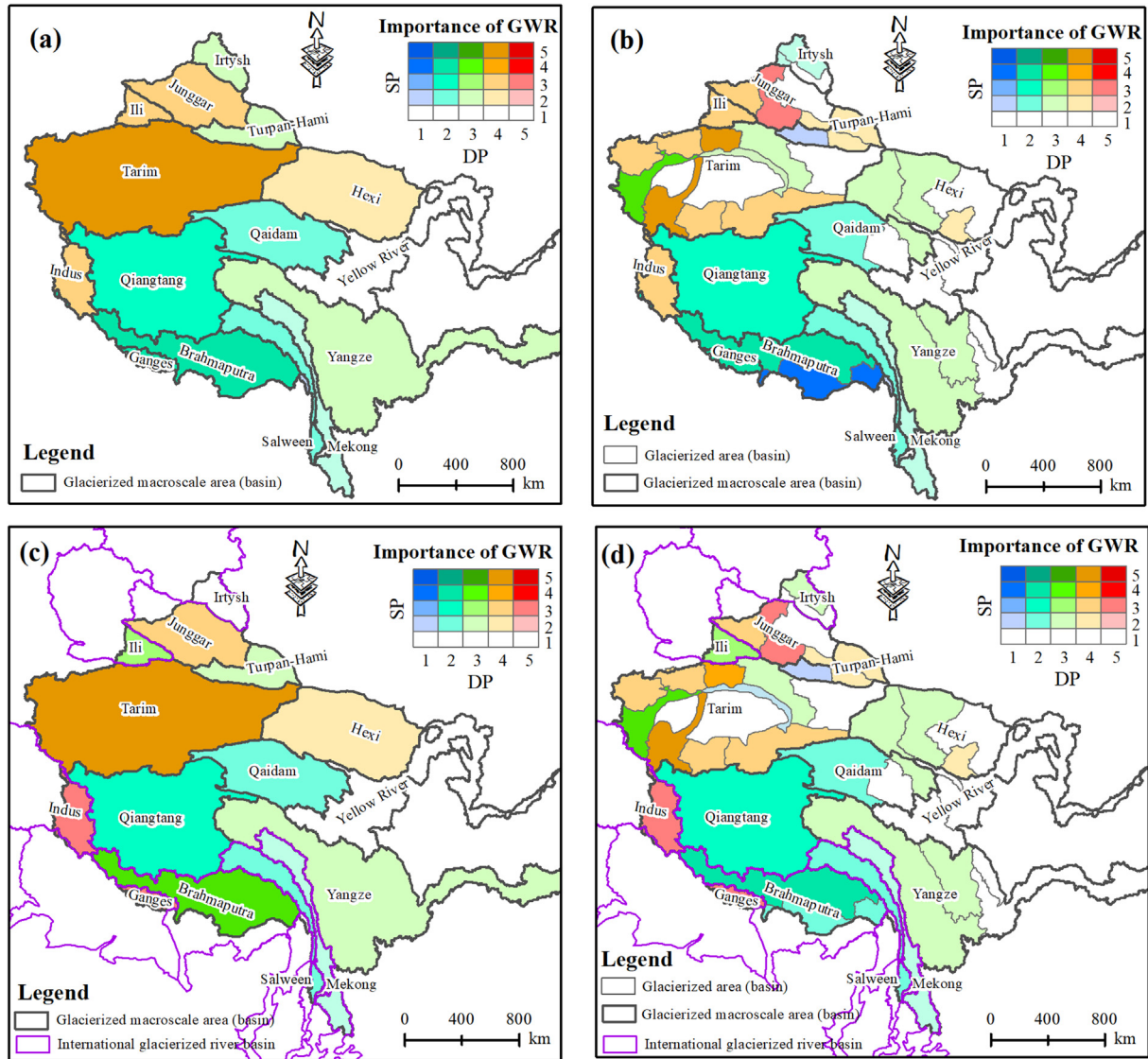


Fig. 2. Regionalization of the importance of China's glacier water resources (GWRs) in terms of their meltwater supply potential (SP) and downstream human dependence (demand potential, DP), (a) glacierized macroscale river basins within China, (b) glacierized microscale river basins within China, (c) glacierized macroscale and (d) microscale river basins across China and in downstream neighbouring countries (SP and DP are classified as very low (1), low (2), medium (3), high (4) and very high (5) based on normalized supply and demand indicators).

If considering the GWR supply to downstream neighbouring countries, China's glacier-affected area expands dramatically (Fig. 1). The glacier coverage of overall glacier-fed areas decreases to 0.5% on average, and the SP also decreases correspondingly, especially in the Ob River basin. Meanwhile, China's total glacier-fed population reached 1.01 billion in 2015, and the proportion of HWSP was 49.6%. Therefore, the DP and the importance of China's GWRs increase substantially when taking into account the water demand of downstream neighbouring countries, especially in the Indus and Ganges river basins (Fig. 2c–d).

3.2. Glacier meltwater service potential (GMSP) and its temporal changes

Based on the threshold of absolute water scarcity (500 m³ per capita per year), we quantified the population equivalent

of China's glacier runoff for 15 macroscale glacierized river basins and 34 microscale basins (the Irtys River basin and its three microscale subbasins were not assessed because they had no available glacier runoff data), representing the maximum annual GMSP (Fig. 3). At the macro-basin scale, the GMSP in Brahmaputra was the largest on average from 2000 to 2010, when the full utilization of GWR could satisfy the basic needs of 29.1 million people. This was followed by Tarim (17.8 million) and Qiangtang (5.1 million). However, the GMSP was low in the Irrawaddy, Yellow River, Turpan–Hami, and Mekong River basins (all less than 0.4 million). At the microbasin scale, basins with large GMSPs, including Yarlung Zangbo (21.3 million), Zangnan (7.9 million), Qiangtang (5.1 million), and Ganges (4.9 million), followed by many branches of the Tarim, such as Yarkant (4.7 million), Muzat (3.9 million), Hotan (2.8 million), Aksu (2.4 million), and Kashgar (2.4 million),

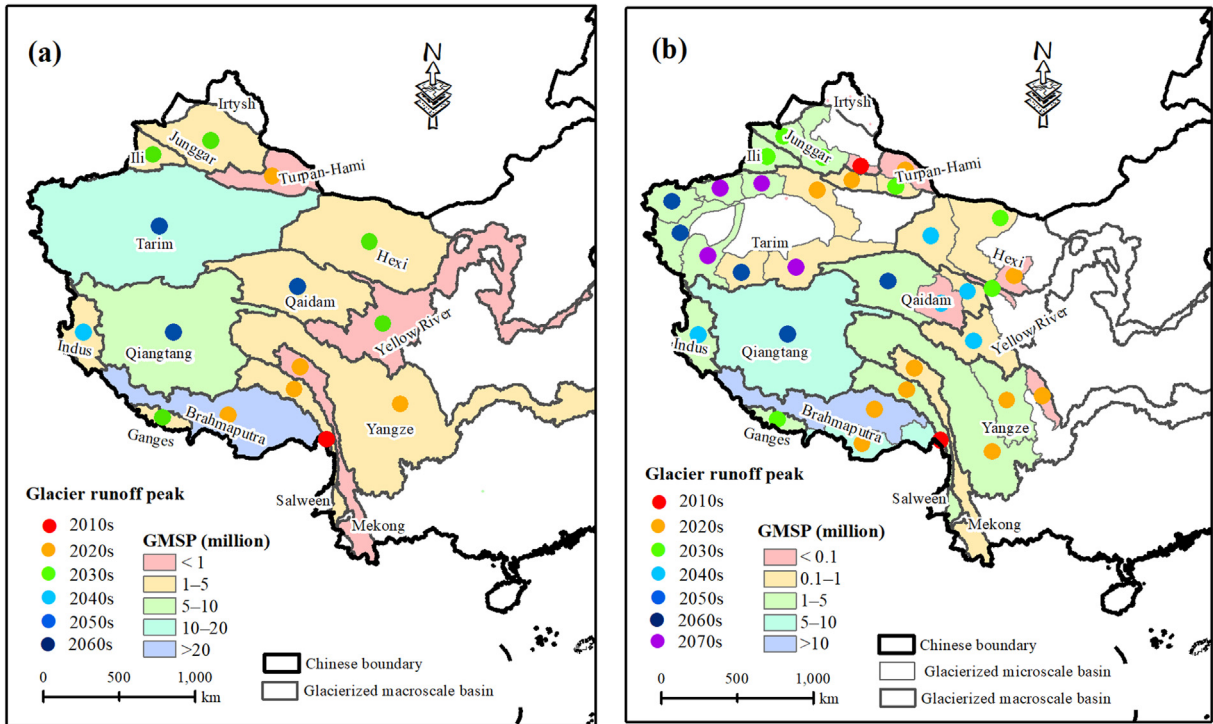


Fig. 3. Glacier meltwater service potential (GMSP) on average during 2000–2010, and timing of the glacier runoff peak under SSP245, (a) glacierized macroscale river basins, and (b) glacierized microscale river basins.

were concentrated in the southern Tibetan Plateau. However, the GMSP in the Fujiang, Eastern Qardam, Junggar East branch, Datong, and Irrawaddy was very low (less than 0.1 million).

Overall, the GMSP in China, excluding the Irtysh River basin, was 79.0 million on average during the period 2000–2010. Under the mid-range SSP245, the GMSP is projected to continue to increase until the 2030s, but after the ‘peak meltwater’, the GMSP will steadily decrease. However, the peak meltwater varies from basin to basin (Fig. 3). There are five macroscale glacierized river basins and 11 microscale subbasins that will see their peak meltwater within the 2020s, and the peak meltwater in the Irrawaddy and Junggar East branches was already reached in the 2010s. Most of these basins are located in the eastern Tianshan Mountains, eastern Qilian Mountains, and southeastern Tibetan Plateau. The Irtysh River basin has likely also reached or will soon see peak meltwater, as most glaciers in this basin are small. However, the GMSP in most basins originating from the Kunlun Mountains, Karakorum, and Qiangtang Plateau will reach their respective maxima in the mid-to-late 21st century. The Hexi, Yellow River, and Junggar River basins will see their maximum GMSP in the 2030s, and the Tarim River basin will see its peak meltwater in the 2060s, but the timing of its peak meltwaters also varies greatly among various subbasins. At the macroscale river basin scale, the GMSP will also peak in the 2030s in the Ili and Ganges River basins, and the Indus River basin will see its peak meltwater in the 2040s.

3.3. Population changes in China's glacier-fed areas

The population living in glacier-fed areas within China increased from 187.1 million in 1980 to 248.2 million people in 2015 (Fig. 4), representing an annual growth rate of only 0.8%. However, during the same period, the total population across only the downstream neighbouring countries fed by China's GWRs increased from 397.0 million to 750.0 million people, representing an annual growth rate reaching 1.8%. Overall, the population living in China's glacier-fed areas (both China and the downstream neighbouring countries) increased from 584.1 million to 998.2 million people during the period 1980–2015. The annual growth rate (1.5%) was consistent with the overall population increase in the world's glacier-fed areas and the global average during the same period (Su et al., 2022a).

At the glacierized river basin scale, the absolute population growth in the glacier-fed basins within China was greater than 1 million during the period 1980–2015 in seven basins: the Yangtze (32.8 million), Yellow River (15.7 million), Tarim (3.3 million), Junggar (2.8 million), Mekong (1.7 million), Hexi (1.6 million), and Yarlung Zangbo (1.0 million) basins. These basins had a combined population of 58.9 million, representing 96.2% of the total population changes in the glacier-fed areas within China. The annual growth rate was greatest in Junggar (1.8%), followed by Yarlung Zangbo (1.6%), Turpan–Hami (1.4%), and Tarim (1.2%). However, the population growth in the Irrawaddy, Indus, Ganges, and Qiangtang Plateau within China was very slow (less than

50,000 people from 1980 to 2015). Notably, the increase in the populations in terms of both absolute and relative growth across the downstream neighbouring countries was far greater than that of glacier-fed basins within China. The results show that the population in most of China's glacier-fed downstream basins increased by more than 100% from 1980 to 2015, especially in the Salween (237.4%) and Indus (182.2%) River basins.

The total population living in the glacier-fed basins within China is projected to continue increasing until a maximum is reached in all SSPs, beyond which the population will gradually decline (Fig. 4). Specifically, the peak population is expected at approximately 2020 under sustainable SSP1, SSP4, and SSP5, reaching 250.3 million, 249.9 million, and 250.3 million, respectively. The peak population in SSP2 (the intermediate pathway for mitigation and adaptation) and SSP3 will occur later (2030) and will reach 252.2 million and 255.5 million, respectively. By the end of the 21st century, the total glacier-fed population within China will decline to 117.9 million, 140.6 million, 188.7 million, 101.7 million, and 118.0 million under SSP1 to SSP5, respectively (Fig. 4a). Taking into account China's glacier-fed population in both domestic and overseas regions, the total population would reach a maximum between 2030 and 2060 in all the SSPs except SSP3, and the total population will reach 1093.4 million, 1264.7 million, 1239.6 million, and 1118.1 million under SSP1, SSP2, SSP4, and SSP5, respectively. For SSP3, the total population in China's glacier-fed region is projected to continue increasing, reaching 1812.2 million in 2100 (Fig. 4b).

At the river basin scale and under the mid-range SSP2 (Fig. 5), the population peak was already reached in approximately 1990 in the downstream Ob River basin (originating from the Altai Mountains), and the population in almost all glacier-fed basins within China is expected to reach a maximum in approximately 2030; then, the total population will decline. The population growth from 2015 to the peak year (2030) is greatest in the Yarlung Zangbo River basin

(7.8%), but the growth in the other river basins within China is generally between 1.5% and 1.7%. However, the downstream Indus basin would see peak population in approximately 2080; the total population in the downstream Mekong, Balkhash Lake, Ganges, and Brahmaputra River basins would continue to increase rapidly until a maximum at around 2050–2060; and the peak population in the downstream Irrawaddy and Salween basins is projected in 2030.

3.4. Opportunities and risks associated with meltwater and population changes

We further analysed the opportunities and risks associated with GMSP and population changes and evaluated their temporal mismatches in the 21st century. As shown in Figs. 6 and 7, the population levels with opportunities (P_{Oi}) and risks (P_{Ri}) at the decadal basin scale (using the 2000s as the first base period) are presented for mid-range SSP245.

In most glacierized river basins on the northern slopes of the Tianshan Mountains, Hexi Corridor and southeastern Tibetan Plateau, the peak meltwater would likely occur earlier than that of the interior and northeastern Tibetan Plateau. Especially in the arid region of Northwest China, GWR plays an extremely important role in those river basins; therefore, the decrease in meltwater after the peak would likely impose severe pressure on local water resources. Among these river basins, the peak glacier water in the Irrawaddy and Junggar east branches was already reached in the 2010s and was reached earlier than their peak populations (expected to be reached in approximately 2030). The adverse combination of decreasing meltwater and increasing population could inevitably exacerbate the risk of water shortages in the 2020s. Our results indicate that an additional approximately 2000 and 5000 people in the Irrawaddy and Junggar east-branch basins, respectively, would be exposed to severe water scarcity due to the combined decrease in glacier meltwater and population increases before 2030. However, for the macroscale

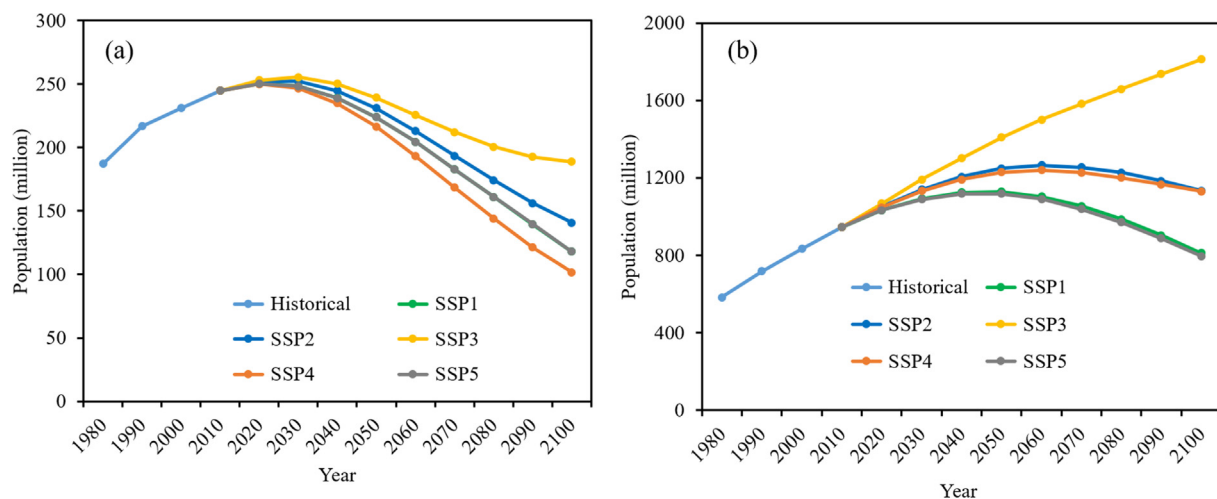


Fig. 4. Population changes in China's glacier-fed basins, historical (1980–2010) and future periods (2020–2100) under the five SSPs, (a) only in China, and (b) in China and downstream neighbouring countries.

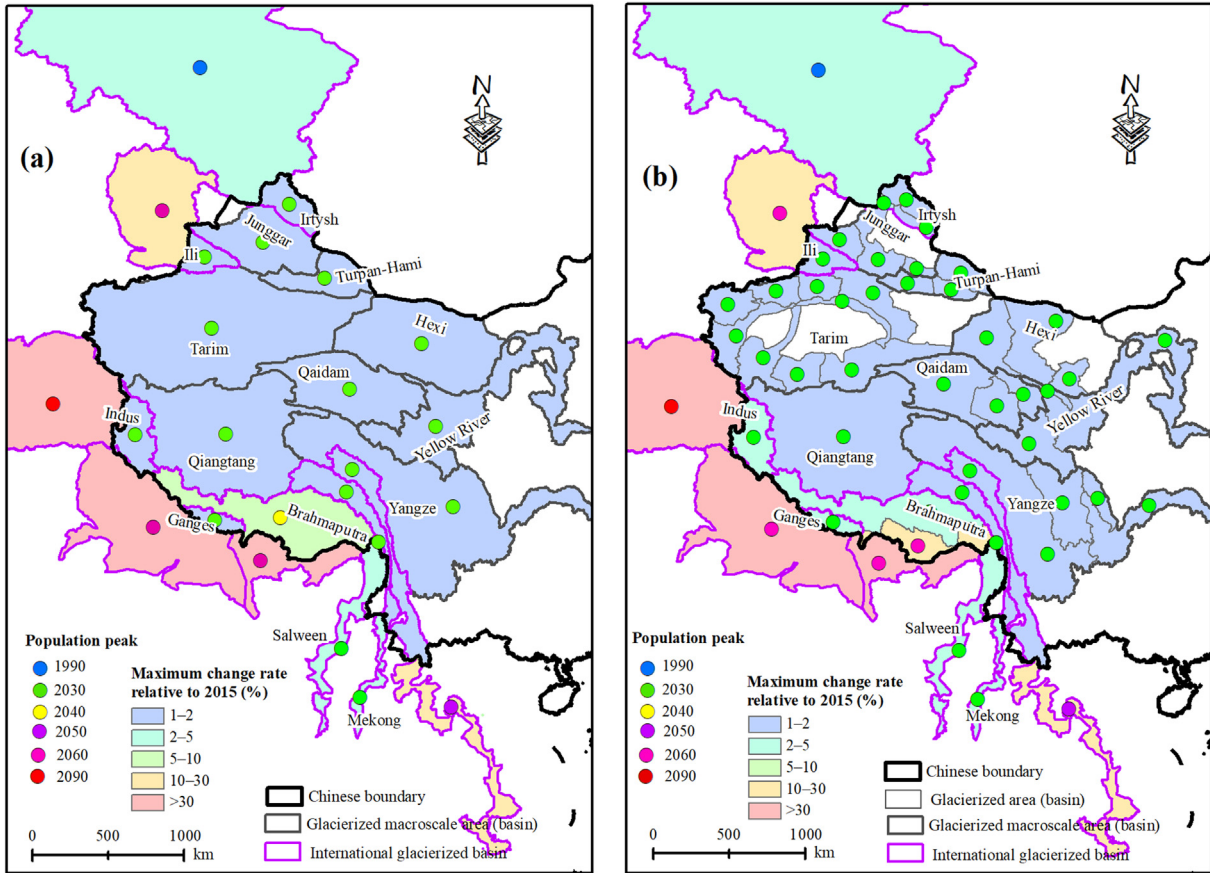


Fig. 5. Population peaks between 1980 and 2100 and their maximum changes relative to 2015 in China's glacier-fed basins under SSP2, (a) glacierized macroscale river basins, and (b) glacierized microscale river basins.

Turpan–Hami, Yangze, Brahmaputra, Salween, and Mekong River basins, peaks in both meltwater and population will likely occur during approximately the same period; in this case, the temporal match would reduce the risk of water shortages to some extent. In addition, the peak meltwater in the Junggar, Hexi, Yellow River, and Ganges River basins will be reached slightly later than its projected population peak, which may relieve some of the water stress during the 2030s. However, after the peak meltwater is reached, the risk of water shortage will intensify gradually.

The peak meltwater in the Tarim River basin will most likely occur during the 2060s, significantly later than its projected population peak (approximately 2030). The opportunities caused by the increase in GMSP in the Tarim River basin can satisfy the basic needs of an additional 1.8 million people from the 2010s to the 2060s. However, after the 2060s, an additional 0.4 million people would be exposed to severe water scarcity due to the decrease in glacier meltwater, even when the population decline has been considered. The mismatch between the GMSP and population changes and the associated opportunities and risks in the Tarim River basin also shows remarkable regional heterogeneity across various microscale subbasins (Fig. 7). Specifically, the peak meltwater in the Kaidu River basin is likely to occur in the 2020s; GMSP in the Kaxgar, Keriya, and Yarkant river basins will see their

peak meltwater in the 2060s; Aksu, Muzat, Hotan, and Qarqan will peak in the 2070s. Later peak meltwater indicates greater opportunities and lesser risks caused by the increase in GMSP, which can not only meet the basic water needs for the increasing population but also greatly relieve the water pressure for those populations living under high water-stressed conditions.

With respect to the interior and northeast Tibetan Plateau, the GMSP in the Qiangtang Plateau is large and will see its peak meltwater (in the 2060s) later than its peak population (approximately 2030). There will be great opportunities associated with the increase in glacier meltwater in the coming decades, but the water demand is projected to be very low due to the low total population and low growth rate; therefore, the actual utilization of glacier water resources would be limited. Peak meltwater in western Qaidam and Qinghai Lake will also occur later than peak population.

Now turning to China's glacier-fed transboundary river basins, the GMSP in the Irrawaddy, Salween, and Mekong River basins is generally low, and GWR is not seen as important in these basins. Therefore, the risks associated with meltwater changes also remain low, although the peak meltwater of these basins is projected to occur earlier than the peak meltwater of the Indus and Ganges river basins. The Ob River basin has a similar pattern: the decreasing meltwater does not

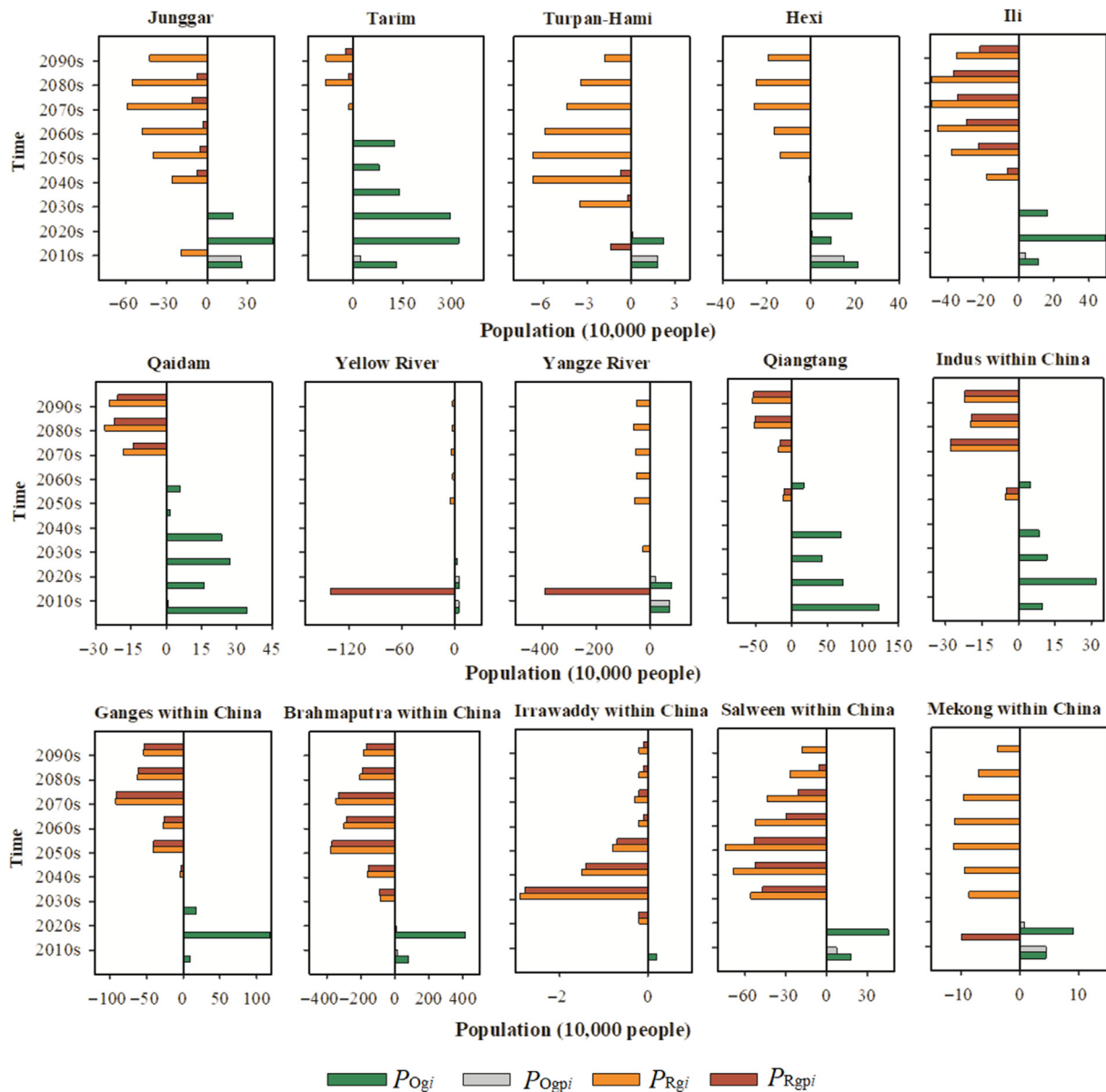


Fig. 6. Opportunities and risks associated only with changes in GMSP (P_{Ogi} and P_{Rgi}) and when jointly affected by GMSP and population changes (P_{Ogpi} and P_{Rgpi}) during the 21st century in 15 glacierized macroscale basins within China.

seriously aggravate pressure on water resources in the downstream countries because the SP is not high, and the peak population has already been reached. The Brahmaputra River basins have very high GMSPs provided by China's glaciers, and here, the peak meltwater is projected to occur within the 2020s, but the downstream peak population will occur in approximately 2060. The decreased meltwater is equivalent to the basic needs of 2.4 million people from the 2030s to the end of the 21st century. Great attention should also be paid to the risks in the Indus and Ganges river basins, where China's GWRs plays an extremely important role, yet the peak meltwater occurs long before the projected peak population downstream. It is estimated that the decrease in meltwater in the Indus (Ganges) River basin after the 2040s (the 2030s) will be equivalent to the basic needs of 0.2 million (0.5 million)

people by the end of the 21st century, but the population will increase by 186.4 million (245.2 million) from 2000 to 2090 (2000–2060). Not only will this mismatch fail to satisfy the basic water demands of the additional population, but it will also impose pressure on water resources for the existing population.

4. Summary and discussion

Under global environmental changes, linking climate-related glacio-hydrological changes to regional socio-economic development is pivotal to regional sustainability. Many studies have investigated the responses of glacier runoff to climate change and the impacts on streamflow in China. However, a national assessment of the combined effects of

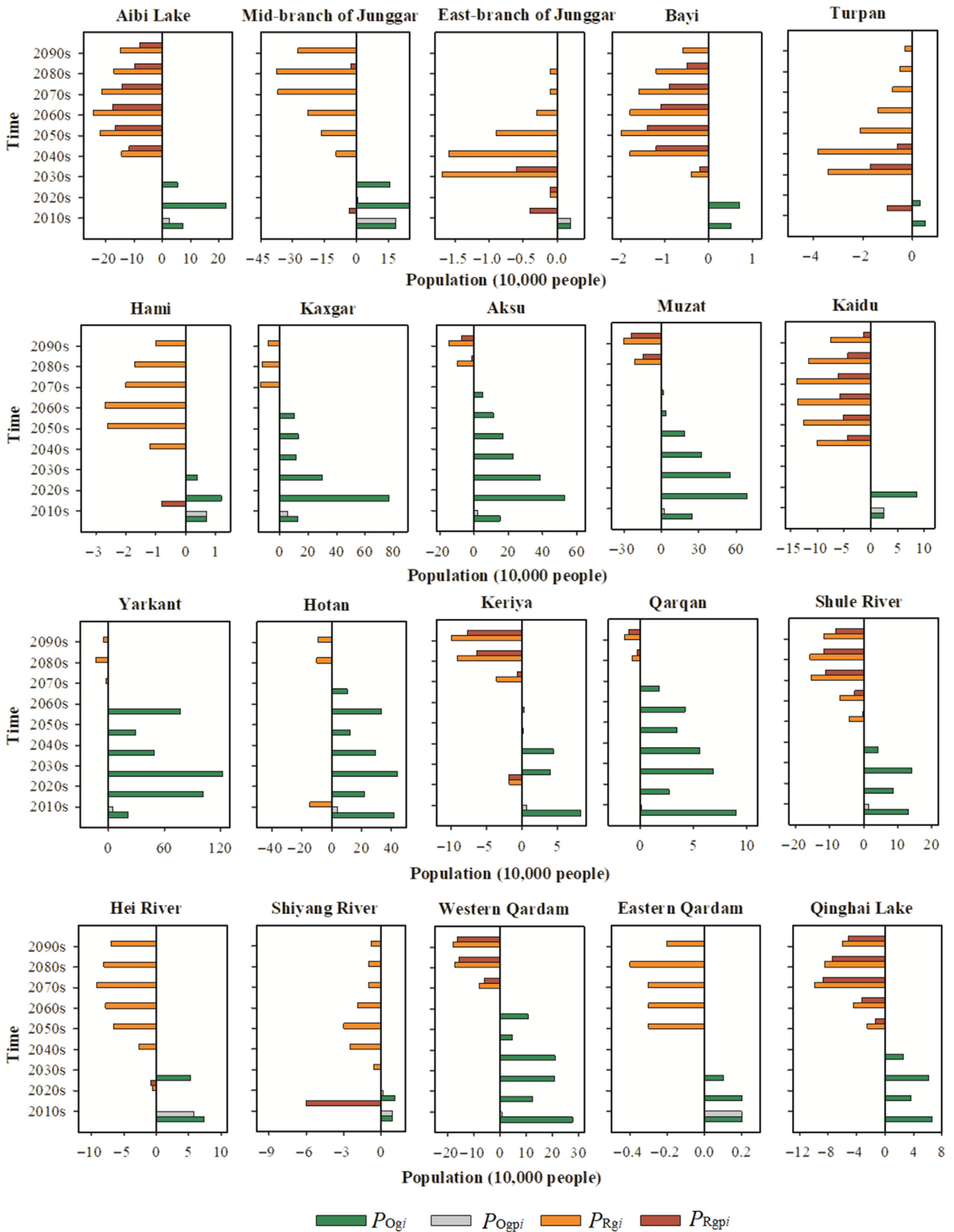


Fig. 7. Opportunities and risks associated only with changes in GMSP (P_{Ogi} and P_{Rgi}) and with the joint effects of GMSP and population changes (P_{Ogpi} and P_{Rgpi}) during the 21st century in 20 glacierized microscale basins within China.

supply and demand potential changes in China's GWRs remains to be conducted. In this study, the importance of China's GWRs was considered regionally in terms of the SP and downstream human dependence (i.e., DP) at multilevel river basin scales. The results show that approximately 248 million people were living in China's glacier-fed areas in 2015, of which nearly 14.8% (36.8 million) were living under high or extremely high water-stressed conditions. China's GWRs plays an important role in four of 14 macroscale glacier-fed basins (Tarim, Junggar, Ili, and Zangxi) and in 11 of 37 microscale subbasins within China due to their high or medium SP and DP. Additionally, DP and the importance of China's GWRs in glacierized transboundary river basins are expected to increase significantly when considering the water demands of downstream neighbouring countries, especially in the Indus, Ganges, and Brahmaputra river basins.

The study also analysed the changes in GMSP and in population dynamics and their temporal (mis-) matches based on the dataset output from the state-of-the-art regional glacier evolution model and climate scenarios, and their associated opportunities and risks were further assessed for various glacierized basins under the mid-range SSP245. The peak meltwater in most glacierized river basins of the eastern Tianshan Mountains, eastern Qilian Mountains, and south-eastern Tibetan Plateau of China had already passed in the 2010s, or their peak meltwater was to be seen within the 2020s, which was slightly earlier than the projected peak population (approximately 2030), leading to a compound risk in terms of decreasing meltwater supply and increasing human dependence in the 2020s. GMSP in the Tarim, Qiangtang Plateau, and Qaidam river basins is projected to peak during the mid to late 21st century, generally after their population peaks. The opportunities offered by the increase in meltwater could relieve regional water pressure and satisfy more water needs, but the mismatch and associated opportunities and risks show significant spatial heterogeneity. In addition, for all the transboundary river basins (except for the Ob (Irtysh) river basin), especially in the Indus and Ganges, the peak meltwater from China's GWRs will likely occur earlier than the projected peak population downstream. The decreasing glacier meltwater will not meet the basic water demands of the additional population and will even impose pressure on water resources for the existing population after the mid-21st century.

This study preliminarily presented a spatially explicit and coherent basin-scale assessment of spatiotemporal (mis-) matches between the supply and demand potentials of China's GWRs for the first time in the 21st century. The study implies that future water resource planning and management in China should be resilient and explicit in both time and space to adequately assess the opportunities and risks associated with changes in meltwater supply and demand. Research should prioritize 'hotspot' basins where GWR plays an important role for human inhabitants. For those transboundary river basins in which China's GWRs is shared across borders with other

countries, there is an urgent need for substantial transboundary cooperation and comanagement to ensure mutual benefits and multilateral progress. However, simulation and projection data for glacier meltwater and human dependence with high spatiotemporal resolution and high precision are still needed to provide more explicit assessments of the supply and demand potentials of China's GWRs and the combined supply and demand effects. Furthermore, in addition to glacier meltwater, the water supply in each glacierized river basin can also be affected by regional precipitation, groundwater, and human activities such as reservoir construction and transregional water diversion. Drainage water is generally consumed in multiple forms, such as agricultural irrigation and ecological, industrial and domestic water usage. Therefore, future studies are expected to fully consider the complex interactions between various components of water supply and demand systems in glacierized river basins.

Declaration of competing interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

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