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Growing hydropower potential in China under 1.5 °C and 2.0 °C global warming and beyond

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Abstract

Renewable energy is the key to reducing greenhouse gas emissions, and is one of the most concerning issues worldwide. China has the largest hydropower potential in the world. Yet, how China's hydropower potential will change under 1.5 °C and 2.0 °C global warming and beyond remains unknown. Here, we find that China's hydropower will increase greatly because of global warming. Gross hydropower potential (GHP) will increase by about one-half compared to the baseline period (1986–2015) under 1.5 °C and 2.0 °C warming, and about two-thirds under 4.5 °C warming. The spatial and temporal changes in GHP will vary largely. GHP will increase relatively more in summer than in winter, and more in Southwest China than in other regions. Compared to GHP, increases in per-capita GHP will be relatively less under 1.5 °C (5%) and 2.0 °C (7%) warming, but of a similar magnitude under 4.5 °C warming (71%). This study provides important information on China's hydropower potential changes under global warming.

1. Introduction

Adverse impacts of climate change have been found globally, such as extreme floods/droughts, heat extremes and wildfires (Alizadeh *et al* 2020, Dethier *et al* 2020, Sherwood 2020, Ball *et al* 2021, Gudmundsson *et al* 2021, Peterson *et al* 2021). Climate change impacts on renewable energy (energy from renewable resources that are naturally replenished) are one of the most concerning issues worldwide because of its important influence on the reduction of greenhouse gas emissions (Gernaat *et al* 2017, 2021, Farinotti *et al* 2019). Among all the renewable energy resources, hydropower is one of the most important energy resources. Hydropower generates about 78% of global renewable electricity and largely depends on water resources that are vulnerable to climate change (Berga 2016).

Studies on renewable energy changes under the 1.5 °C and 2.0 °C global warming levels set by the Paris Agreement have been carried out in several regions (Donk *et al* 2018, Meng *et al* 2020). In Europe, Tobin *et al* (2018) found that global warming has limited impacts on solar photovoltaic systems. They reported that wind power potential will decrease slightly (<5% for 1.5 °C and 2.0 °C warming), and that changes in hydropower potential will be within 10% (1.5 °C), 15% (2 °C) and 30% (3.0 °C). Several studies have investigated hydropower changes in river basins in China (Liu *et al* 2016, Li *et al* 2020, Guo *et al* 2021, Zhang *et al* 2021). However, how China's hydropower will change under the 1.5 °C and 2.0 °C global warming levels remains unknown.

China has the largest hydropower potential in the world, accounting for 13.8% of the world total (Hoes *et al* 2017), and hydropower electricity accounts for about 20% of China's total electricity currently (Feng *et al* 2019). China is the most populous country and is one of the fastest-growing economies on the globe. With the increasing population and enlarging economic volume, the country's electricity demand will be boosted dramatically in the future (Duan *et al* 2021). China has announced that the country's carbon emissions have to peak before 2030 and that

China has to become carbon neutral before 2060 (Mallapaty 2020). To achieve these ambitious carbon emission reduction goals, China has to take advantage of the large hydropower potential to meet future electricity demand (Mallapaty 2020), which requires an understanding of the hydropower variations in the future.

Here, we investigated the spatial and temporal changes of China's hydropower potential under 1.5 °C and 2.0 °C global warming and beyond for the first time. We examined seven large rivers/regions (figure 1(a)) where China's hydropower bases are located (Feng *et al* 2019). Examinations of hydropower potential changes were performed at both river-basin and provincial levels. In addition, per-capita hydropower potential changes were investigated under the Representative Concentration Pathway (RCP) 2.6—Shared Socio-Economic Pathway (SSP) 1, RCP6.0—SSP3, and RCP8.5—SSP5 scenarios. Our study has important implications for future hydropower exploration in China.

2. Methodology

2.1. The datasets

Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE) precipitation and air temperature were used for the historical period (Yatagai *et al* 2012). Because the data ended in 2015, data from 1986 to 2015 were used as the 30 year baseline period. Other meteorological data for the baseline period were from the China Meteorological Forcing Dataset (CMFD) (He *et al* 2020), including air pressure, specific humidity, wind speed, downward shortwave radiation and downward longwave radiation. Both APHRODITE and the CMFD are based on China's precipitation and meteorological gauge data. Future climate data were from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b) (Frieler *et al* 2017). The bias corrections for ISIMIP2b data were carried out by the ISIMIP team (www.isimip.org/gettingstarted/isimip2b-bias-correction/), and we used the corrected data in this study. ISIMIP2b data have been commonly used in hydrology related studies globally (e.g. Gernaat *et al* (2021), Gudmundsson *et al* (2021), Woolway *et al* (2021)). Therefore, we also used ISIMIP2b in our study. The general circulation models (GCMs) in ISIMIP2b are equally important because no information shows which GCM is superior to others, and equal weight was assigned to them when calculating averages of the modeled data (Gudmundsson *et al* 2021). All the climate data were on a daily basis and the GCM data were re-gridded into 0.1° cells to match the spatial resolution of the baseline period climate data. More information about the datasets used and the time periods corresponding to different global warming levels can be found in the supporting information. In this study, the 4.5 °C warming scenario corresponds to RCP8.5, which is the business-as-usual extreme climate scenario, and was therefore used here.

2.2. The model simulation

The Water and Energy Budget-based Distributed Hydrological Model with improved Snow physics for Global simulation (WEB-DHM-SG) (Qi *et al* 2022b) was used in this study to simulate discharge in China. Schematic descriptions of the WEB-DHM-SG model are shown in figure S1 in the supporting information. The WEB-DHM-SG combines the advantages of WEB-DHM-S (Wang *et al* 2017) and CaMa-Flood (Yamazaki *et al* 2013). The WEB-DHM-S integrates the simple biosphere scheme (SiB2) land surface model, a hydrological model based on geomorphology developed by Yang (1998 and a physically based snowmelt model (Shrestha *et al* 2010). CaMa-Flood is a hydraulic model for large-scale studies, and can simulate discharge, flood inundation, water level, etc. The discharge simulation was performed on a daily scale based on the daily scale climate data. The WEB-DHM-SG model was calibrated and validated on a monthly scale, considering that human activities (such as reservoir operations) have influenced the daily scale discharge in many regions in China (Yang *et al* 2021, Qi *et al* 2022b). The hydrological gauges used are shown in figure S2 in the supporting information. Calibrated parameters are shown in table S1 in the supporting information. The regions outside the seven large river basins/regions in figure 1(a) use default model parameters (www.futurewater.eu/), but this has a minor influence on our results because all the large hydropower bases are located within the seven large river basins/regions where the model was calibrated and validated. The model used is a distributed hydrological model, and the input climate data are also spatially distributed. The spatially distributed climate data are used as the input of the hydrological model to simulate discharge and hydropower changes. Therefore, the unevenly distributed warming and the effects on discharge and hydropower potential are considered in our study. More details about the model calibration and validation can be found in the supporting information.

2.3. The gross hydropower potential (GHP) calculation

The GHP (unit: W) is calculated using equation (1)

$$\mathrm{GHP} = Q \cdot h \cdot g \cdot \rho \quad (1)$$

where Q is discharge ($m^3\ s^{-1}$); h is the hydraulic head (m); g is the acceleration of gravity (9.81 m s^{-2}); and ρ is the density of water (1000 kg m^{-3}). GHP was simulated based on the daily discharge, and its

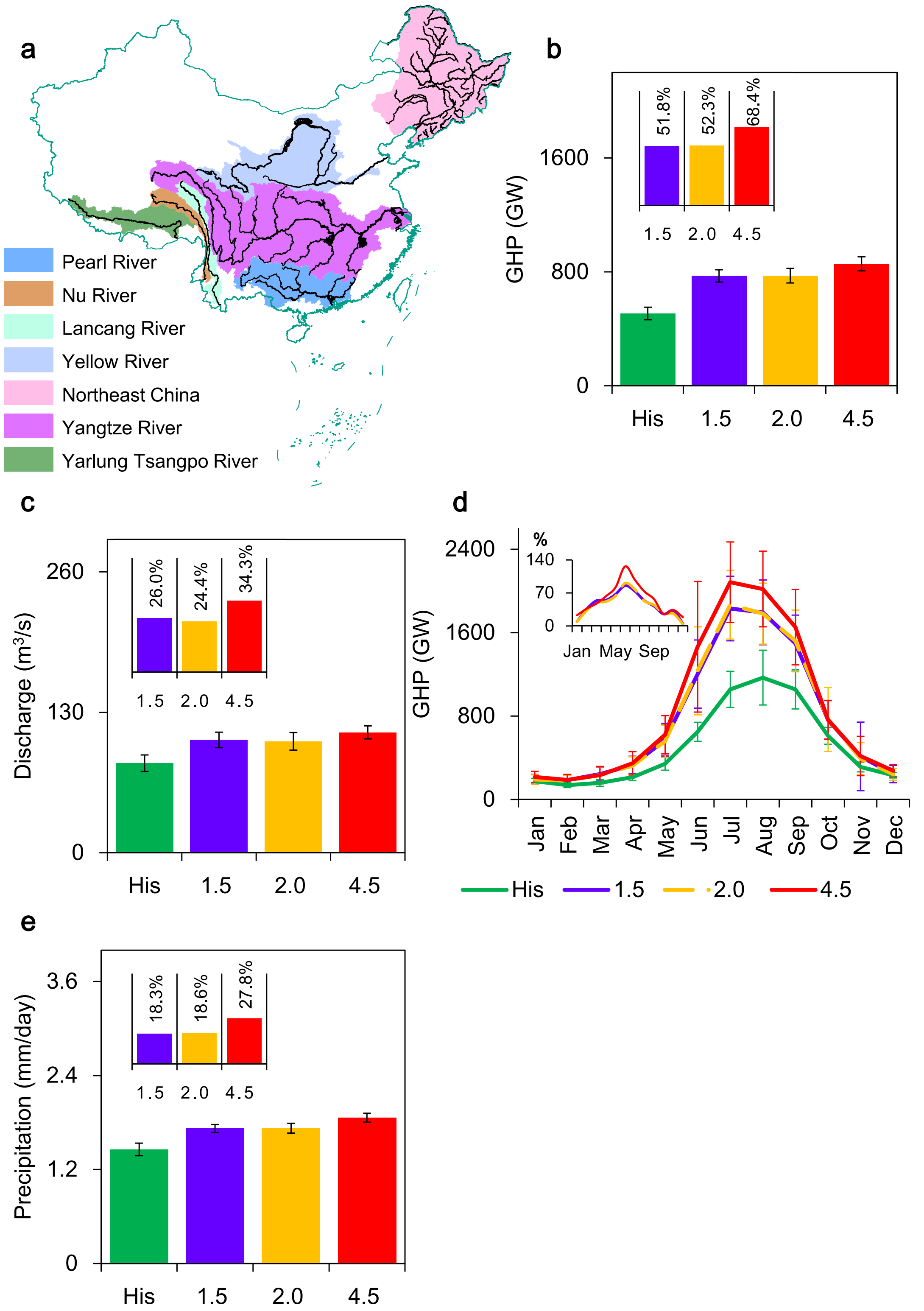

Figure 1. Main river basins and regions (a), gross hydropower potential (GHP) (b), (d), discharge (c) and precipitation (e) in China under the 1.5 °C, 2.0 °C and 4.5 °C global warming levels. The percentage values in (b) and (c) represent the relative changes compared to the baseline period. His = baseline period (1986–2015). The error bars represent the standard deviation.

monthly and annual changes were studied. Per-capita GHP (p-GHP) was calculated as GHP divided by the number of the population. The p-GHP is an indicator that considers both the supply and demand sides (van Ruijven et al 2019), and therefore is investigated in this study. The MERIT digital elevation model data were used in the hydraulic head calculation (Yamazaki et al 2019). More information about GHP simulation, validation and the population data used can be found in the supporting information.

3. Results

3.1. Gross hydropower potential changes in the whole of China

China's hydropower potential will increase as a result of global warming. Under 1.5 °C warming, GHP will increase by about one-half compared to the baseline period (figure 1(b)). GHP under 2.0 °C warming levels will be slightly higher than that of the 1.5 °C warming scenario. Generally, GHP will increase steadily under the global warming levels from 1.5 °C to 4.5 °C with a 0.5 °C step (see figures S3(a) and (b) in the supporting information). GHP will be up to 848.7 GW under 4.5 °C warming, which is about two-thirds higher than that in the baseline period. The increase in GHP is because of the larger discharges (figure 1(c)). Projected discharges will increase by 26.0%, 24.4% and 34.3% under 1.5 °C, 2.0 °C and 4.5 °C warming levels, respectively, which is due to the increases in precipitation (figure 1(e)). The disproportional changes in GHP, discharge and precipitation are due to their spatial distribution differences and hydraulic head. The increased GHP equals 1.83, 1.85 and 2.42 gigatonnes of CO_2 emission reduction per year under the 1.5 °C, 2.0 °C and 4.5 °C warming levels, respectively. In 2019, China's total carbon emissions were 10.17 gigatonnes (https://ourworldindata.org/co2/country/china). If the increased GHP in the future warming climate is used to generate electricity, the CO_2 emissions will be reduced by at least 18%.

The seasonal variations of GHP will also change largely (figure 1(d)). GHP will peak in July under the global warming scenarios, which differs from that in the baseline period (i.e. August). The peak GHP will be 1831.5 GW and 1867.6 GW under 1.5 °C and 2.0 °C warming, respectively, which are more than 50% (56.8% for 1.5 °C and 59.8% for 2.0 °C) higher than that in the baseline period (1168.4 GW). Under 4.5 °C warming, the peak GHP (2083.8 GW) will be more than 75% (78.4%) higher. During the winter period (mainly in December and January), GHP increases will be relatively less on average (6.9% for 1.5 °C, 6.4% for 2.0 °C and 20.8% for 4.5 °C) compared to other months. GHP increases are the largest on average in the summer (mainly in June, July and August): 70.9% (1.5 °C), 73.3% (2.0 °C) and 98.8% (4.5 °C).

3.2. Gross hydropower potential changes in sub-regions of China

GHP changes vary greatly among rivers/regions in China. Of the seven river basins/regions, the Yangtze River has the largest GHP in both the baseline and future warming periods (figure 2(a)), primarily due to the largest discharge (figure 2(b)) among all the regions. Under 1.5 °C and 2.0 °C warming, GHP in the Yangtze River will increase by about 30% (figure 2(c)) compared to the baseline period (197.6 GW); under 4.5 °C warming, it is expected to increase by about 40% (figure 2(c)). GHP in the Yangtze River accounts for about one-third of the total in China under 1.5 °C (33.3%), 2.0 °C (32.9%), and 4.5 °C (32.4%) warming periods, and they are a little lower than its share in the baseline period (38.9%), which is due to the increase in the total GHP in the whole of China. The Yarlung Tsangpo River has the second largest GHP, and the largest increase among the regions in the future (figure 2(c)). Under 1.5 °C, 2.0 °C and 4.5 °C warming levels, GHP in the Yarlung Tsangpo River will increase by 68.7%, 71.7% and 91.2%, respectively, compared to the baseline period (88.6 GW). GHP in the Yarlung Tsangpo accounts for about one-fifth of the total in China under the 1.5 °C (19.4%), 2.0 °C (19.7%) and 4.5 °C (19.8%) warming periods, and they are higher than its share in the baseline period (17.4%). Among all the river basins/regions, discharge increases in the Yarlung Tsangpo River are the highest under 1.5 °C, 2.0 °C and 4.5 °C warming levels (figure 2(d)), which result in the largest increases in GHP.

The total GHP of the Yangtze and the Yarlung Tsangpo Rivers will account for 52.7% (1.5 °C), 52.6% (2.0 °C) and 52.1% (4.5 °C) of China's total, about 4% less than that in the baseline period (56.3%). The decrease in the share is due to GHP increases in other rivers/regions. Comparatively, the discharge in the Pearl River is larger than that in the Yarlung Tsangpo River, but the elevation drop in the Pearl River is lower than that in the Yarlung Tsangpo River (see figure S4 in the supporting information). Northeast China has the lowest GHP and the least changes among all the rivers/regions studied due to the relatively low discharge and hydraulic head.

3.3. Spatial variations of gross hydropower potential

GHP varies largely in space. The southwest river source region (including the Yarlung Tsangpo River, Nu River, Lancang River, and Upper Yangtze River) has larger GHP than other regions (figure 3(a)), which is the combined results of hydraulic head and discharge (figure 4(a)). Under 1.5 °C warming (figure 3(c)), GHP will become larger in the southwest river source region, the middle reach of the Yellow River, the central part of Northeast China, etc. Under 2.0 °C (figure 3(d)) and 4.5 °C (figure 3(e)) warming levels, the spatial distribution of GHP changes is similar to the results of 1.5 °C warming levels. Generally, the spatial distribution of GHP changes is similar to discharge changes under 1.5 °C (figure 4(c)), 2.0 °C (figure 4(d)) and 4.5 °C (figure 4(e)) warming levels.

Provincial GHP is larger in the southwest provinces (figure 3(b)), such as Tibet (147.3 GW),

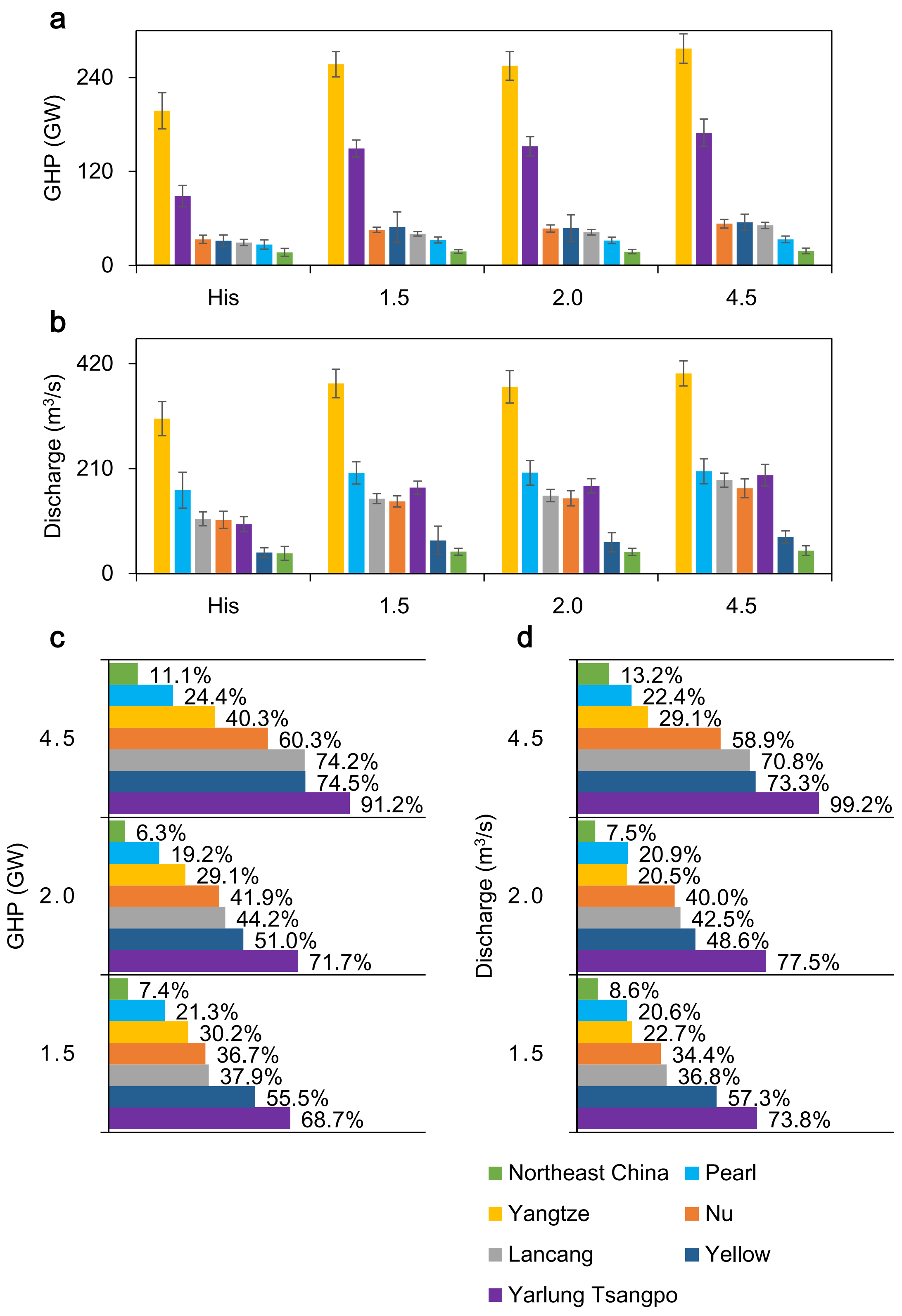

Figure 2. GHP (a), (c) and discharge in the large river basins/regions (b), (d) in China during the baseline, 1.5 °C, 2.0 °C and 4.5 °C global warming periods. (c) and (d) The relative changes compared to the baseline period. His = baseline period (1986–2015). The error bars represent the standard deviation.

Sichuan (95.6 GW) and Yunnan (83.0 GW). GHP in the southwest provinces accounts for 64.1% of the total in China. GHP in the Qinghai province is 19.8 GW, which is larger than in other provinces, except for the southwest provinces. Under 1.5 °C (figure 3(f)), 2.0 °C (figure 3(g)) and 4.5 °C (figure 3(h)) warming levels, the Tibet province will benefit the most, and GHP in Tibet will increase by

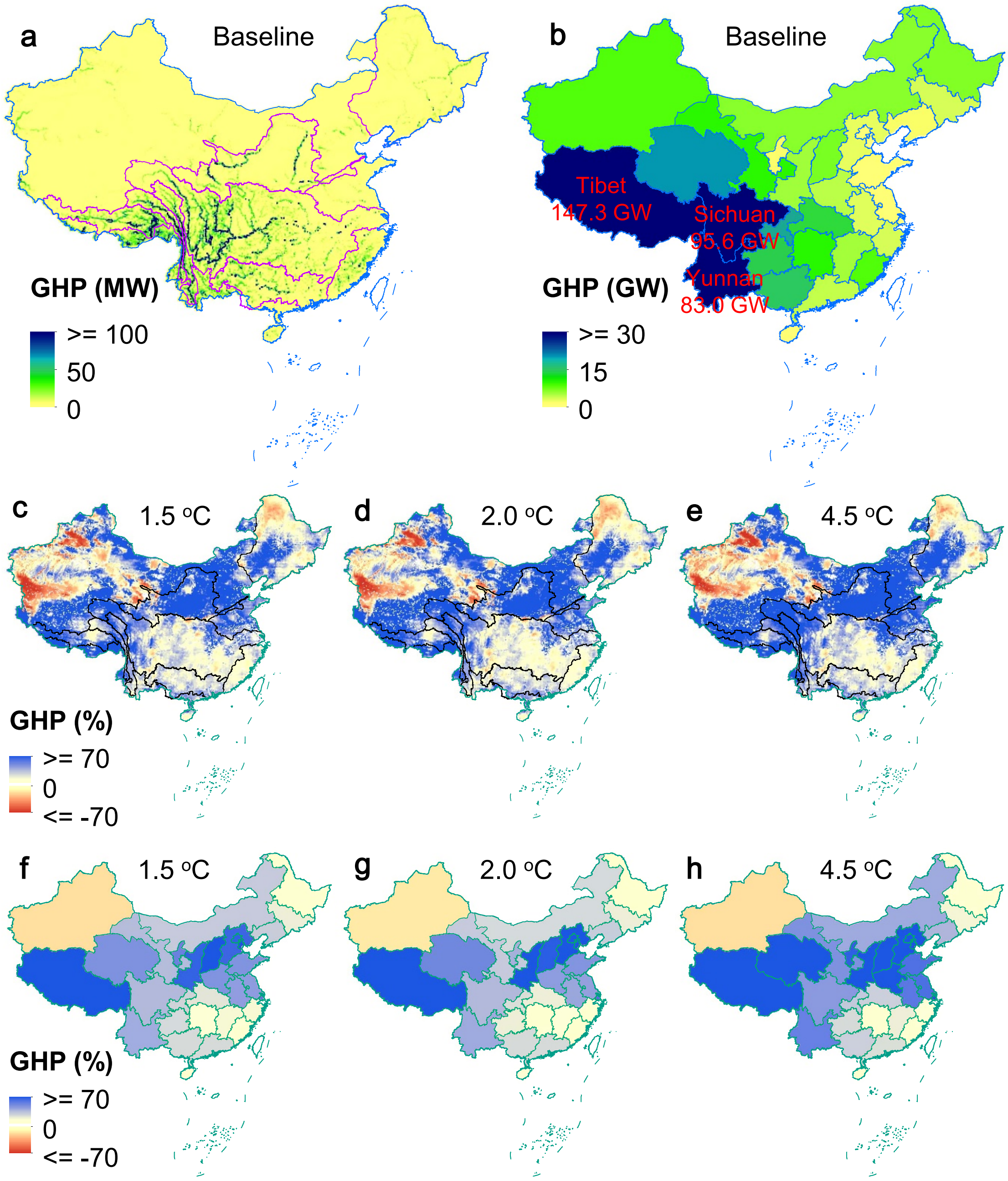

Figure 3. Spatial variations of GHP in China. (c)–(h) The relative changes in GHP compared to the baseline period under the 1.5 °C, 2.0 °C and 4.5 °C global warming levels. The names of the provinces are shown in the supporting information.

96.9%, 100.4% and 124.8%, respectively. In Sichuan province, GHP will increase by 32.0%, 31.5% and 43.4% under 1.5 °C (figure 3(f)), 2.0 °C (figure 3(g)) and 4.5 °C (figure 3(h)) warming levels, respectively. In the Yunnan province, the increases are 36.3%, 37.5% and 52.8%. In the Qinghai province, the increases are 46.3%, 49.6% and 79.6%.

3.4. Variations of per-capita gross hydropower potential

The p-GHP will increase slightly under 1.5 °C (5.4%) and 2.0 °C (6.7%) warming (figure 5(a)), and will increase substantially (71.3%) under the 4.5 °C warming levels due to the combined results of the increasing GHP and decreasing population. The increased p-GHP equals 0.19, 0.24 and 2.57 million tonnes CO_2 emission reduction per year, respectively. Generally, p-GHP will increase consistently from 1.5 °C to 4.5 °C global warming with a 0.5 °C step (see figures S3(c) and (d) in the supporting information). The southwest river source region has a larger p-GHP than other regions (figure 5(b)), except for the northern part of Northeast China and some regions in the Xinjiang province, where the population is sparse. The p-GHP in the Tibet province is the largest (7.9 GW) among all provinces (figure 5(c)), followed by the Xinjiang (0.8 GW) and Qinghai provinces (0.8 GW). The p-GHP in the Sichuan province is

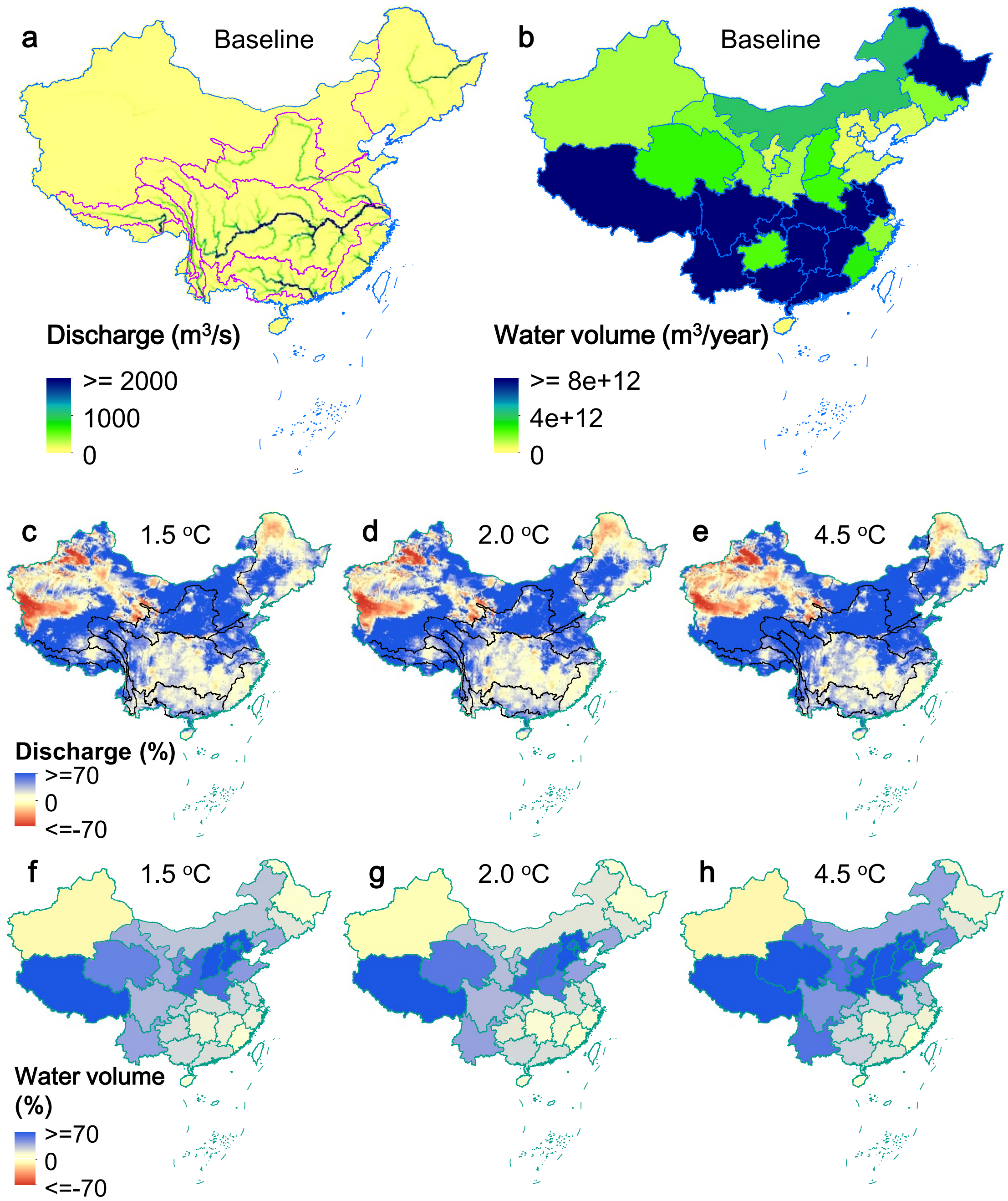

Figure 4. Discharge and water volume in China. (c)–(h) The relative changes compared to the baseline period under the 1.5 °C, 2.0 °C and 4.5 °C global warming levels.

0.2 GW, and it is 0.09 GW in the Yunnan province (figure 5(c)).

Under 1.5 °C warming, p-GHP will increase in most of the regions (figures 5(d) and (g)). Similar patterns will occur for 2.0 °C (figures 5(e) and (h)) and 4.5 °C (figures 5(f) and (i)) warming levels. Under 1.5 °C and 2.0 °C warming levels, p-GHP will become lower in several provinces in South and East China (such as Hubei, Hunan, Anhui, Jiangsu, Jiangxi, Guangdong, Guangxi, Guizhou) and the Liaoning province in Northeast China; under 4.5 °C warming, only the Hainan province will become lower in terms of p-GHP.

4. Discussion

The United Nations' sustainable development goals have advocated building a low-carbon and sustainable future. China is the largest carbon emissions country in the world (Sun *et al* 2021). To achieve sustainable development goals and reduce carbon emissions, China is planning to generate electricity largely from clean sources (Mallapaty 2020). Hydropower is one of the choices for China since China has the largest hydropower potential among all the countries worldwide. At present, the installed capacity of hydropower accounts for about 49% of China's total

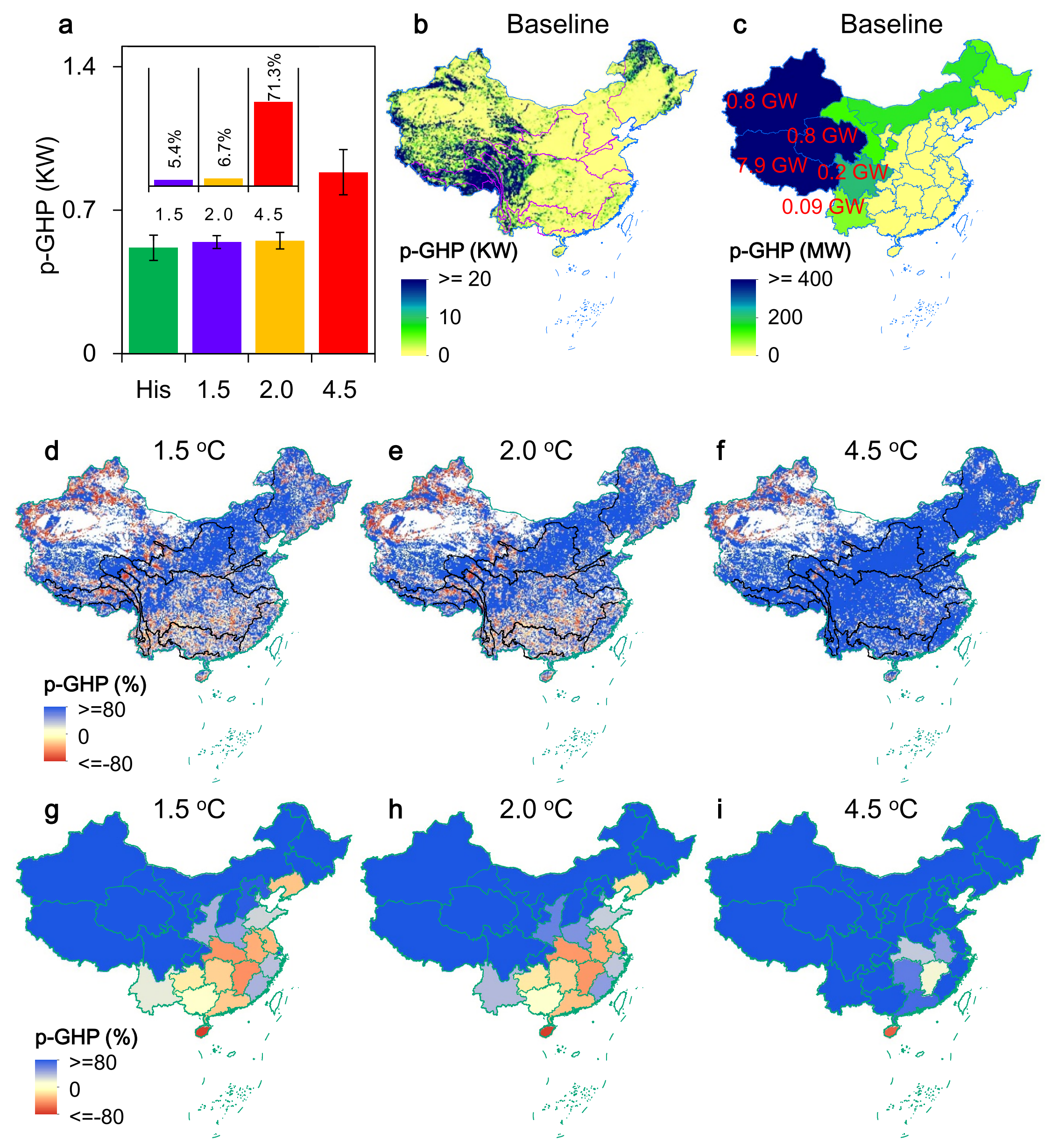

Figure 5. The p-GHP in China during the baseline period, 1.5 °C, 2.0 °C and 4.5 °C global warming periods. The percentage values in (a) represent the relative changes in p-GHP compared to the baseline period. (d)–(i) The spatial distribution of relative changes. His = baseline period (1986–2015). The error bars represent the standard deviation.

hydropower potential (Sun *et al* 2019), and hydropower accounts for 20% of China's electricity production. Therefore, there is still large potential for China to explore hydropower. The increasing hydropower potential we found in this study will favor China's clean energy development policy and the 2030 and 2060 carbon emissions reduction ambitions to fight climate change. Under the 2.0 °C warming scenario, the hydropower potential in China would be about 6782 terawatt hours a year, which is equivalent to 4.9 gigatonne carbon emissions reduction and 317 billion US dollars in economic value a year if it is fully explored. According to Mallapaty (2020), to reduce the use of fossil fuels and achieve net zero carbon emissions, China's electricity production will reach at least 14 800 terawatt hours a year before 2060. The baseline period hydropower potential could contribute 30% of the electricity production; under the 2.0 °C warming scenario, it would contribute 46%. The increased 16% hydropower potential would be an important energy source that could be used to replace other energy sources, such as fossil fuels. China's growing hydropower potential that we found in this study could motivate more hydropower exploration in the future due to the large potential in electricity production and carbon emission reduction. The consistently increasing hydropower potential we found in this study assures the sustainability of hydropower development, which could be an important support to China's long-term and persistent hydropower investment. Similar studies and results have not been carried out and reported before.

To achieve the 1.5 °C global warming goal, China has developed many policies to reduce carbon emissions. Duan *et al* (2021) suggested that China's carbon emission peak time would be between 2035 and 2040 for the 1.5 °C global warming target if there were no extra carbon emission reduction policies. The suggested time period is obviously later than the announced 2030 carbon emission peak time by the Chinese government. Therefore, extra policies have to be developed. The largely increasing GHP projected under the 1.5 °C global warming scenario would provide such an opportunity to create new approaches to reach the peak carbon emissions on time.

To raise the share of hydropower in the electricity system, the Yangtze River and the Yarlung Tsangpo River are two hotspots for hydropower development. The Yangtze River is the largest hydropower base in historical and future periods. The hydropower increase in the Yarlung Tsangpo River will be the largest among all the river basins in the future. Currently, there are several large hydropower plants in the Yangtze River, but large hydropower plants in the Yarlung Tsangpo River are rare. At the end of 2020, the Chinese government changed the hydropower dam construction plan for the Yarlung Tsangpo River, and announced that China would construct a large hydropower dam in the downstream region. Our results could be a strong support for the dam construction plan in the Yarlung Tsangpo River, and suggest that more efforts should be devoted to the development of hydropower in the Yarlung Tsangpo River, which could largely increase the share of hydropower electricity in China's energy system and reduce carbon emissions. For example, under the 2.0 °C warming scenario, the hydropower potential in the Yarlung Tsangpo River would be about 1333 terawatt hours a year, accounting for up to 20% of China's total, which is equivalent to 1 gigatonne carbon emissions reduction in a year. The Yarlung Tsangpo River flows downstream of India, Bangladesh and Bhutan. Hydropower development in the Yarlung Tsangpo River should consider the upstream and downstream appeals and minimize the regional disputes (Freeman 2017). In addition, the Yarlung Tsangpo River is one of the most ecologically vulnerable areas in the Tibetan Plateau, and hydropower development in this river should solve the ecological conservation issue first (Xu and Pittock 2020).

Tibet, Sichuan and Yunnan provinces have the largest hydropower among all the provinces in China and, therefore, there should be more focus on them for the exploration of the increasing hydropower. The three provinces are located in southwest China, but power demand in East and South China is the largest because of the large population and high gross domestic product. Under 1.5 °C and 2.0 °C warming scenarios, per-capita hydropower will become lower in many South and East China provinces. Therefore, further development of the west-to-east electricity transmission project is important for the transport of the growing hydropower from southwest China to South and East China.

Although hydropower will benefit from the overall increase in discharge under the warming climate, the perverse impacts should also be paid attention to. For example, the increasing discharge and melting glaciers and snow will lead to compound glacier lake outburst floods in the Tibetan Plateau (Li *et al* 2022, Qi *et al* 2022a). In addition, the increasing discharge will cause landslides in mountainous regions and will result in rising dam failure risk because of overtopping and erosion (Li *et al* 2022).

Increasing population will raise water assumptions in irrigation, industrial and domestic water uses, etc. However, we studied the hydropower potential, which was based on naturalized discharge. The potentially increasing water assumptions will not influence our results. In this study, we used the bias-corrected climate projections from ISIMIP2b. The ISIMIP2b climate data can be considered reliable, as the studies by Gernaat *et al* (2021), Gudmundsson *et al* (2021), and Woolway *et al* (2021) suggested. Therefore, the use of the ISIMIP2b climate data is acceptable in this study.

5. Conclusion

Here, we studied the changes in China's hydropower potential under the different global warming levels. This study could provide important information on China's hydropower development amid the trend of shifting to renewable energy. The following conclusions are presented based on this study.

First, China's hydropower potential will increase greatly because of global warming. GHP will increase by about one-half compared to the baseline period (1986–2015) under 1.5 °C and 2.0 °C warming levels, and about two-thirds under 4.5 °C warming levels.

Second, GHP will increase more in summer than winter and more in Southwest China than in other regions. GHP in Tibet (the Yarlung Tsangpo River) will increase the most among all provinces (among all the river basins). The total GHP of the Yangtze and the Yarlung Tsangpo Rivers will account for more than half of China's total.

Third, compared to GHP, increases in per-capita GHP will be relatively less under 1.5 °C (5%) and 2.0 °C (7%) warming levels, but of a similar magnitude under 4.5 °C warming (71%) levels.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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