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Undermined co-benefits of hydropower and irrigation under climate change

Ying Meng [a,b], Junguo Liu [b,*], Zifeng Wang [b,c], Ganquan Mao [b], Kai Wang [b], Hong Yang [d]

[a] School of Environment, Harbin Institute of Technology, Harbin 150090, China
[b] School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen, 518055, China
[c] Department of Geography, The University of Hong Kong, Hong Kong SAR, China
[d] Department of Systems Analysis, Integrated Assessment and Modelling, Swiss Federal Institute for Aquatic Science and Technology (Eawag), Dübendorf, Switzerland

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ABSTRACT

Dam construction is mostly aimed for multiple functions, including irrigation water provision, hydropower, and some others that bring substantial social benefits. However, global warming impacts on the interaction of the positive outcomes of damming remain little known, particularly in terms of the sustainability of their co-benefits, whereby investigating the different impacts of global warming scenarios of 1.5 °C and 2 °C has been a hotspot in water resources and energy research worldwide. This study used an integrative analysis based on a hydrological, techno-economic and agricultural modeling framework to evaluate the effects of global warming scenarios of 1.5 °C and 2 °C on the co-benefits between hydropower and irrigation in the Mekong River basin. The results show the declined hydropower generation and irrigation water supply in the Mekong River basin under 1.5 °C and 2 °C warming scenarios. The co-benefits between the hydropower and the irrigation is more undermined by the global warming of 2 °C relative to 1.5 °C in the Mekong River basin. Moreover, the changes of co-benefits are sensitive to the consideration of the protected areas in the basin. With the consideration of the protected areas, the co-benefits would be enhanced by 2 °C global warming compared to 1.5 °C global warming. Therefore, it is critical for decision-makers to consider the tradeoffs between the environment and dam construction for ensuring energy and food security under global warming scenarios.

1. Introduction

Hydropower, as renewable and climate-friendly energy, makes substantial contributions to meet ascending global power demands (Almeida et al., 2019; Latrubesse et al., 2017; Owusu and Asumadu--Sarkodie, 2016), accounting for 73% of global renewable power supply (Zarfl et al., 2019). Accelerating hydropower-driven dam constructions at an unprecedented rate worldwide are often associated with disputes on their detrimental environmental effects (Maavara et al., 2020; Sunday, 2020; Waldman et al., 2019). However, hydropower dams could also provide multiple purposes, including drinking water supply, flood control, irrigation supply. As a result, the expansion of hydropower dam constructions has been considered as a potential solution to multiple challenges in the context of global changes (Meng et al., 2020; Zarfl et al., 2019; Zhou et al., 2015).

The nexus assessment is increasingly recognized as a assist to achieve the Sustainable Development Goals (SDGs) (Bergendahl et al., 2018;Liu et al., 2017). Dams can play a significant role in the nexus assessment as hydropower generation and irrigation water supply are often the major two functions among many (Hoang et al., 2019). However, global warming with projected higher climate variability and more extreme weather conditions would affect the availability of water resources, and thus alter the hydropower generation (Arnell and Gosling, 2013; Hoang et al., 2019) and the water-energy-food nexus (Zhang et al., 2017; van Vliet et al., 2016). Therefore, the relationship (competition or complementary) between hydropower and irrigation is expected to change under global warming due to climate change-induced alterations in water resources (van Vliet et al., 2016; Zeng et al., 2017).

In the Paris Agreement two strategical adaptation plans were released: holding 2 °C increase in the global average surface temperature above pre-industrial levels and pursuing efforts to limit 1.5 °C increase in the temperature before 2100 (UNFCCC, 2015). To that end, investigating the different impacts of 1.5 °C and 2 °C global warming scenarios has been an important topic in water resources and energy

* Corresponding author.
E-mail addresses: liujg@sustech.edu.cn, liujg@sustech.edu.cn, water21water@yahoo.com, junguo.liu@gmail.com (J. Liu).

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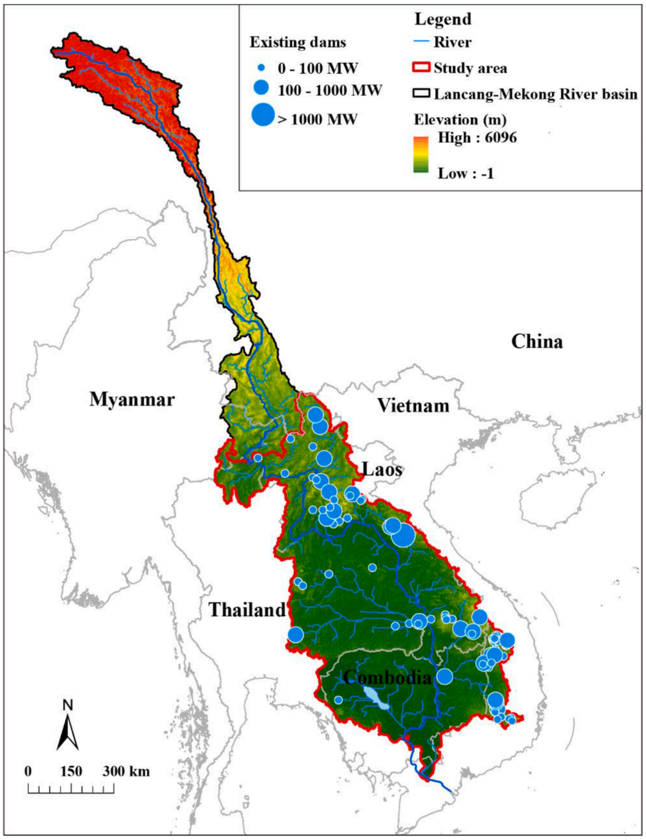

Fig. 1. The location of existing dams in the Mekong River basin. The dam data is from Water, Land and Ecosystems (WLE, 2018).

research (Ove et al., 2018; Tobin et al., 2018). Nevertheless, there is a lack of research on the effects of different scenarios of global warming about the water-energy-food nexus (Meng et al., 2020; Zhang et al., 2018).

The Lancang-Mekong River, the eighth largest river by discharge (475 km^3 annually), originates in the Qinghai-Tibet Plateau and passes through Myanmar, Vietnam, the Lao People's Democratic Republic (hereafter Laos), Cambodia, and Thailand (Fig. 1). The Lancang-Mekong River basin is geographically divided into two sub-sections: the mountainous Lancang River basin in China with a low population density, and the flat and fertile Mekong River basin with a high population density. About 82% of the river's annual discharge comes from the Mekong River basin (MRC, 2010). Although the Mekong River basin is mainly covered by lowlands and floodplains, the hydropower potential of the Mekong River basin is still considerable, which is estimated at 60,000 MW (MRC, 2011). However, the installed capacity in the Mekong River basin is around 24,000 MW (WLE, 2018) and only nearly 40% of hydropower potential has been exploited so far (Kuenzer et al., 2013). Currently, the Mekong River basin is undertaking an unparalleled rate of dam construction (Fig. 1) due to the rapid socioeconomic development and ascending power demands (Pokhrel et al., 2018b). Furthermore, it has been estimated that 460 km^3/year Mekong river flow is consumed for irrigation requirement (MRC, 2005). The water supply for agriculture is responsible for 80%~90% of all water abstraction in the Mekong River basin (MRC, 2005). Rice is the dominate crop (MRC, 2005, 2010b) and accounts for the largest maximum consumption of fresh water in this region (Cosslett and Cosslett, 2017; Pokhrel et al., 2018a). Rice is the main staple food for the local population and a quarter of the world's rice exports is produced from this region (Cramb, 2020).

In general, there is a positive synergy relationship between hydropower generation and irrigation supply (Zeng et al., 2017). Storage for hydroelectricity generation can improve water supply for irrigation. Dams could be operated to build up a high hydraulic head and then release the water to produce hydropower. At the same time, hydropower dams can provide reliable water resources for irrigation supply during the dry season (Zewdie et al., 2019). The constructed infrastructure and its operation contribute to the complementarity between hydropower generation and irrigation supply.

The objective of the study is to analyze the effects of global warming scenarios on the co-benefits between hydropower and irrigation. We focus on the effects of 1.5 °C and 2 °C global warming scenarios on the

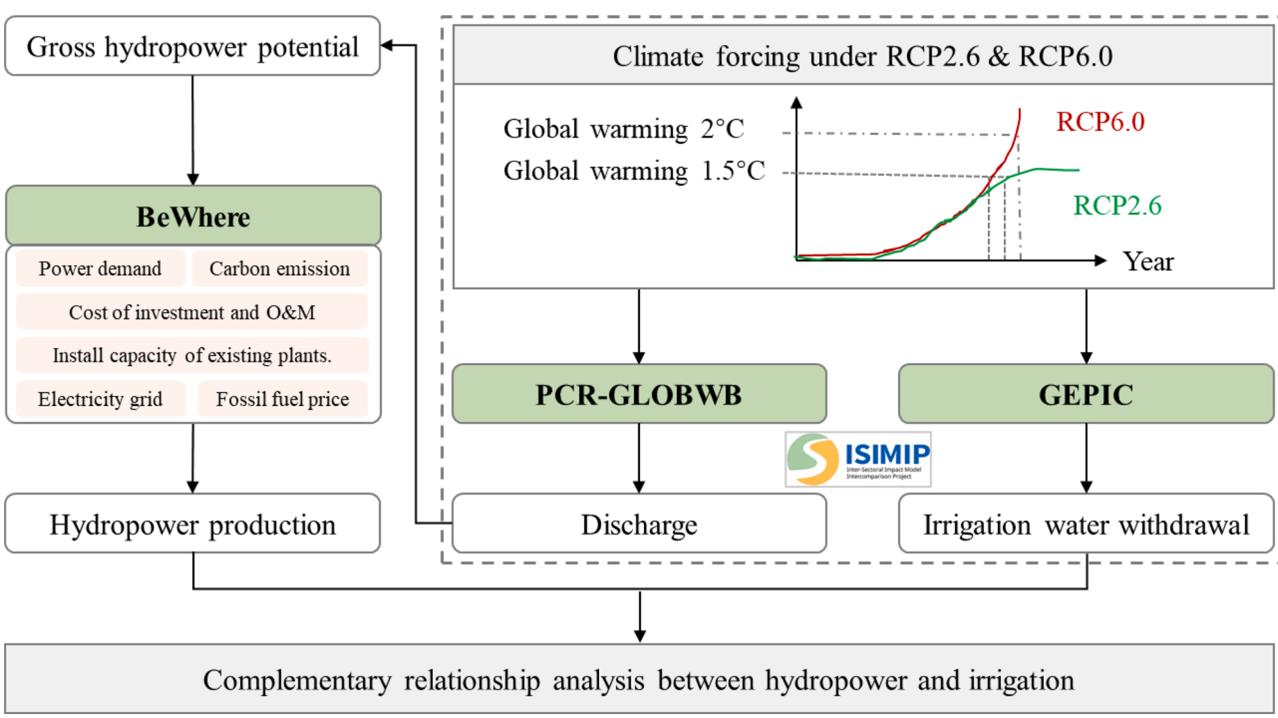

Fig. 2. The schematic of the complementary relation analysis framework.

co-benefits between hydropower production and irrigation water supply for rice in the Mekong River basin, where is undergoing an unprecedented rate of dam construction (Fig. 1) (Pokhrel et al., 2018b). An integrative analysis based on hydrological, techno-economic, and agricultural model framework is used for the analysis. The study results could provide support of selecting optimal sites for hydropower plants under 1.5 °C and 2 °C global warming. Moreover, this research would facilitate building a basis for decision-makers on water, energy, and food security under 1.5 °C and 2 °C global warming. The understanding of the water-energy-food nexus could help to achieve the Sustainable Development Goals (SDGs) such as Goal 2 “Zero hunger” and Goal 7 “Affordable and clean energy”. Although the study focuses on the Mekong river basin, the analytical approaches developed and knowledge learnt concerning the co-benefits of hydropower generation and irrigation for food production under different climate change scenarios are useful for other regions in the world facing the similar challenges to manage their water resources for energy and food security today and in the future.

2. Materials and methods

In this study, the analysis of co-benefits between hydropower and irrigation in Mekong River basin under 1.5 °C and 2 °C global warming levels is built on the simulated discharge, hydropower production and irrigation water supply. The framework consists of two parts: (1) the computation of hydropower production based on the simulated discharge under different climate scenarios. (2) the co-benefits analysis between hydropower production and irrigation water supply for rice under different global warming scenarios compared to the pre-industrial period. The hydropower production with the consideration of protected areas in the basin will also be investigated for comparison with the natural hydropower generation estimated. The flowchart of this study is shown in Fig. 2.

2.1. Discharge and irrigation water supply projections

The discharge and rice irrigation water demand data used in this study are simulated by the PCR-GLOBWB and GEPIC models. The data are supplied by the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP). All the simulations were conducted for each grid cell of 0.5° at daily time step. For the hydrological simulation data, discharge from the PCR-GLOBWB hydrological model (version 2) are used (Wada et al., 2014; Sutanudjaja et al., 2018). Since the PCR-GLOBWB model only provided the total irrigation water demand without separating the water demand for different crops. The rice irrigation water demand is therefore obtained from the GEPIC model, a crop model included also in the ISIMIP project with the same climate forcing data as PCR-GLOBWB. The validation and distribution of discharge are shown in Supplementary material Figure S1, Figure S2 and Figure S3. The PCR-GLOBWB model is suitable to estimate discharge at large scale (Van Beek and Bierkens 2008). We assume that irrigation water supply can meet the irrigation water demand in the Mekong River basin, due to the sufficient surface water resources in the region (Pokhrel et al., 2018a). The irrigation water supply is the water quantity provided by surface water and groundwater for irrigation purposes (FAO, 2020). The irrigation demand (W_d) was calculated based on the irrigation efficiency (E_i) and irrigation water requirement (W_r) (Eq. (1)) (Döll and Siebert, 2002). Irrigation water requirement (W_r) is the quantity of water needed to meet the rice crop water requirement (FAO, 1997). Irrigation water requirement (W_r) was simulated by GEPIC and the data are extracted from ISIMIP.

$$W_d = \frac{W_r}{E_i} \tag{1}$$

Bias-corrected climate forcing data for driving the PCR-GLOBWB and GEPIC model were provided by the Coupled Model Inter-comparison Project (CMIP5) outputs (Frieler et al., 2017). The PCR-GLOBWB and GEPIC simulations were forced by the different Global Climate Models (GCMs, including GFDL-ESM2M, IPSL-CM5A-LR, MIROC5, and HadGEM2-ES) individually in CMIP5 under RCP2.6 and RCP6.0. The analysis is in the basis of the average of the four simulation results to reduce uncertainties caused by climate forcing data. Shared Socioeconomic Pathways (SSPs) describes socioeconomic futures and SSP2 describes a middle-of-the-road scenario concerning population and mitigation and adaptation challenges for the 21st century (Fricko et al., 2017). The population growth and socioeconomic development began from 2005 onwards according to the SSP2 storyline and were associated with RCP2.6 (representing strong mitigation scenario under SSP2) and RCP6.0 (representing no mitigation scenario under SSP2). The RCP2.6-SSP2 is closest to the global warming limits agreed upon in Paris (Fricko et al., 2016)

Global warming of 1.5 °C will come up in 2036 under RCP2.6 and in 2033 under RCP6.0 based on the average of four GCMs, while 2 °C global warming scenario would come up in 2056 under RCP6.0 (Shi et al., 2018; Frieler et al., 2017). RCP2.6 based simulation showed that the temperature increase will not reach the global warming level of 2 °C in our simulated period (Fricko et al., 2017; van Vuuren et al., 2011). Thus, the simulated discharge and water requirement in 2036 (2033) under RCP2.6 (RCP6.0) emission pathway is used to estimate the gross hydropower potential and water demand under the scenario of 1.5 °C global warming. And the discharge data in 2056 under RCP6.0 emission pathway is used to estimate the gross hydropower potential at the scenario of 2 °C global warming. The time period 1971–2010 was selected as the baseline on behalf of the historical period.

2.2. Hydropower generation modeling

2.2.1. Hydropower potential calculation

Gross hydropower potential is the basis for quantifying the global warming impacts on hydropower. The gross hydropower potential is an essential input for the estimation of hydropower generation. The gross hydropower potential was estimated for each grid cell based on discharge, elevation and other flow information (Eq. (2)). The discharge was at a spatial resolution of 50 km. The elevation and other flow information were from HydroSHEDS at a special resolution of 500 m (Lehner et al., 2008). The discharge and elevation were then resampled by ArcGIS to the same resolution (around 25 km) to estimate the gross hydropower potential and fed into BeWhere. Then the distance from every grid to the lowest grid along the downstream paths was calculated. Moreover, we estimated gross hydropower potential under 1.5 °C global warming under RCP2.6 emission pathway and 1.5 °C and 2 °C global warming levels under RCP6.0 emission pathway, respectively.

$$P = g \cdot \rho \cdot \Delta H_i \cdot Q \tag{2}$$

in the Eq. (2), P represents the hydropower capacity (in W), g represents average of gravitational acceleration (m/s^2), ρ represents water density (kg/m^3), ΔH_i represents the difference elevation between the grid i and the lowest grid (m), and Q represents annual discharge (m^3/s). The maximum hydropower generation is attained when all the discharge is used for hydropower production.

2.2.2. Identifications of the optimal hydropower siting

The BeWhere model is able to find out the optimal sites and sizes of hydropower plants by the minimum expense and has been widely used in biomass energy systems (Wetterlund et al. 2012; Khatiwada et al. 2016). However, BeWhere was seldom applied in hydropower decision and development (Meng et al., 2020; Mesfun et al., 2018, 2017).

We applied BeWhere to investigate optimal sites and size for setting new hydropower plants under 1.5 °C and 2 °C scenarios of global warming considering electricity grids, electricity demand, investment of launching hydropower plants, existing plants, the expenses of manage-

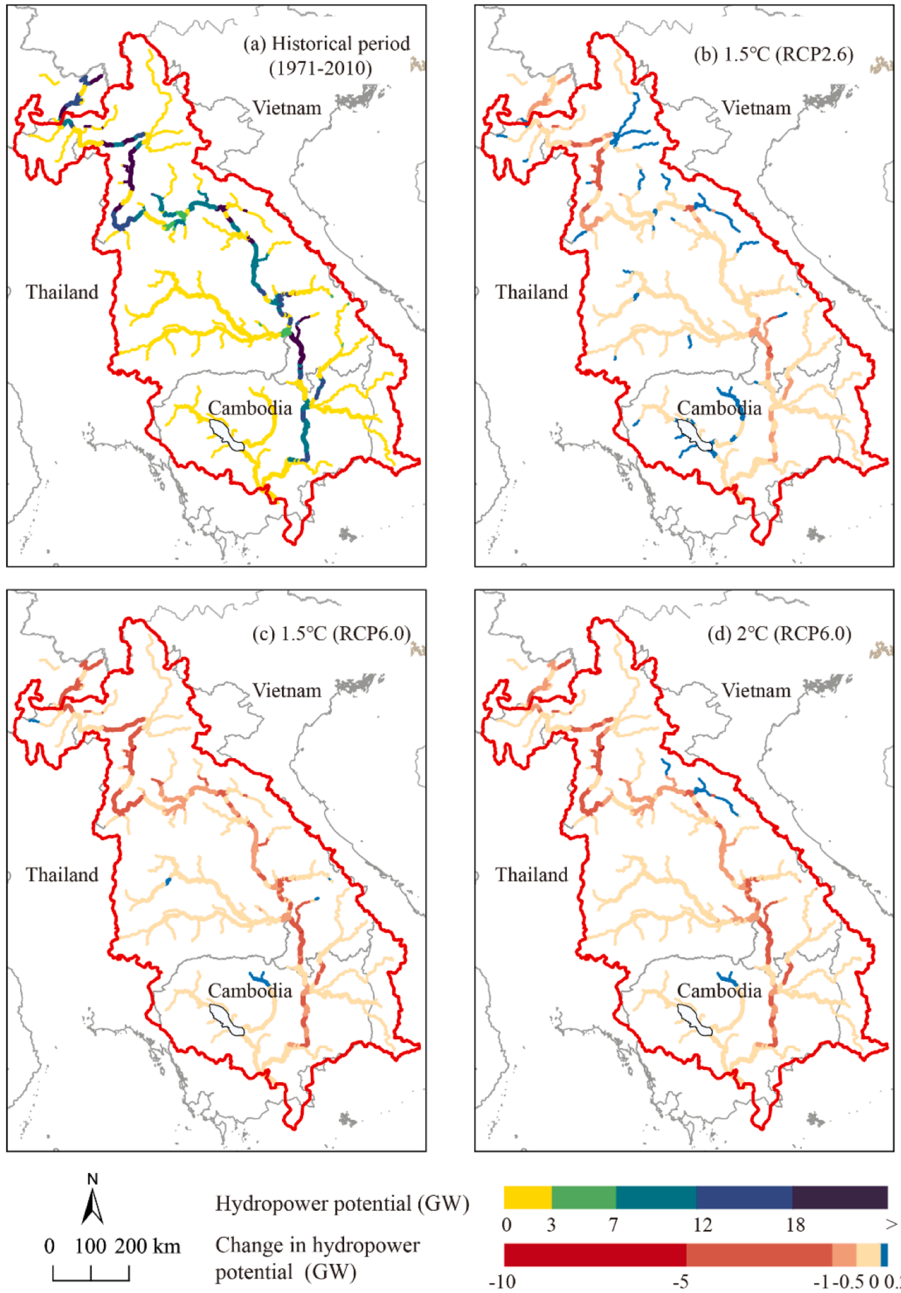

Fig. 3. Hydropower potential (GW) during the historical period, and the differences between the historical period and the 1.5 °C and 2 °C global warming scenarios.

ment and repair, and the cost caused by transmission distances (Leduc et al., 2008, 2010) . BeWhere is configurated at 25 km spatial resolution to explore the least-expense (C_{tot}) of the entire hydropower supply chain:

$$C_{tot} = C_{supply\ chain} + E_{supply\ chain} C_{CO_2} \tag{3}$$

in Eq. (3), $C_{supply\ chain}$ represnet the expense of the hydropower supply chain (variable), $E_{supply\ chain}$ represents the emissions of supply (variable), and C_{CO_2} represent the expense of CO_2 emission (parameter). $C_{supply\ chain}$ includes expenses of setup, management and repair of hydropower plants and the cost caused by transmission distances.

Expense of establishing new hydropower plants commonly depends on the size of the hydropower plants. The capital expense ranges from 2.5 to 10 k$/kW while the capacity of hydropower plant is smaller than 1 MW, from 2 to 7.5 k$/kW while the capacity is between 1 and 10 MW and from 1.75 to 6.25 k$/kW while the capacity is greater than 10 MW (BlackandVeatch, 2012).The entire expense of management and repair for hydropower production is a mean range. The range varies between 30 and 185 $/MWh based on the capacity of a hydropower plant. The expense varies from 55 to 185 $/MWh when the capacity is smaller than 1 MW, from 45 to120 $/MWh when the capacity is between 1 and 10MW and from 40 to 110 $/MWh when the capacity is greater than 10 MW. The variable management and repair expense for hydroelectricity is 6 $/MWh (BlackandVeatch, 2012). The transmission expense is defined as the entire expense of setting up transmission lines connecting an existing power transmission hub to new hydropower plants. We considered the expense to connect different transmission line is 1 $/km-kW supposing its economic lifetime of 40 years (Mesfun et al., 2018). The distance between the potential hydropower plant sites and the nearest hub is estimated by a network map of hub routes (OpenStreetMap, 2015), which is parameterized to calculate the expense in the model.

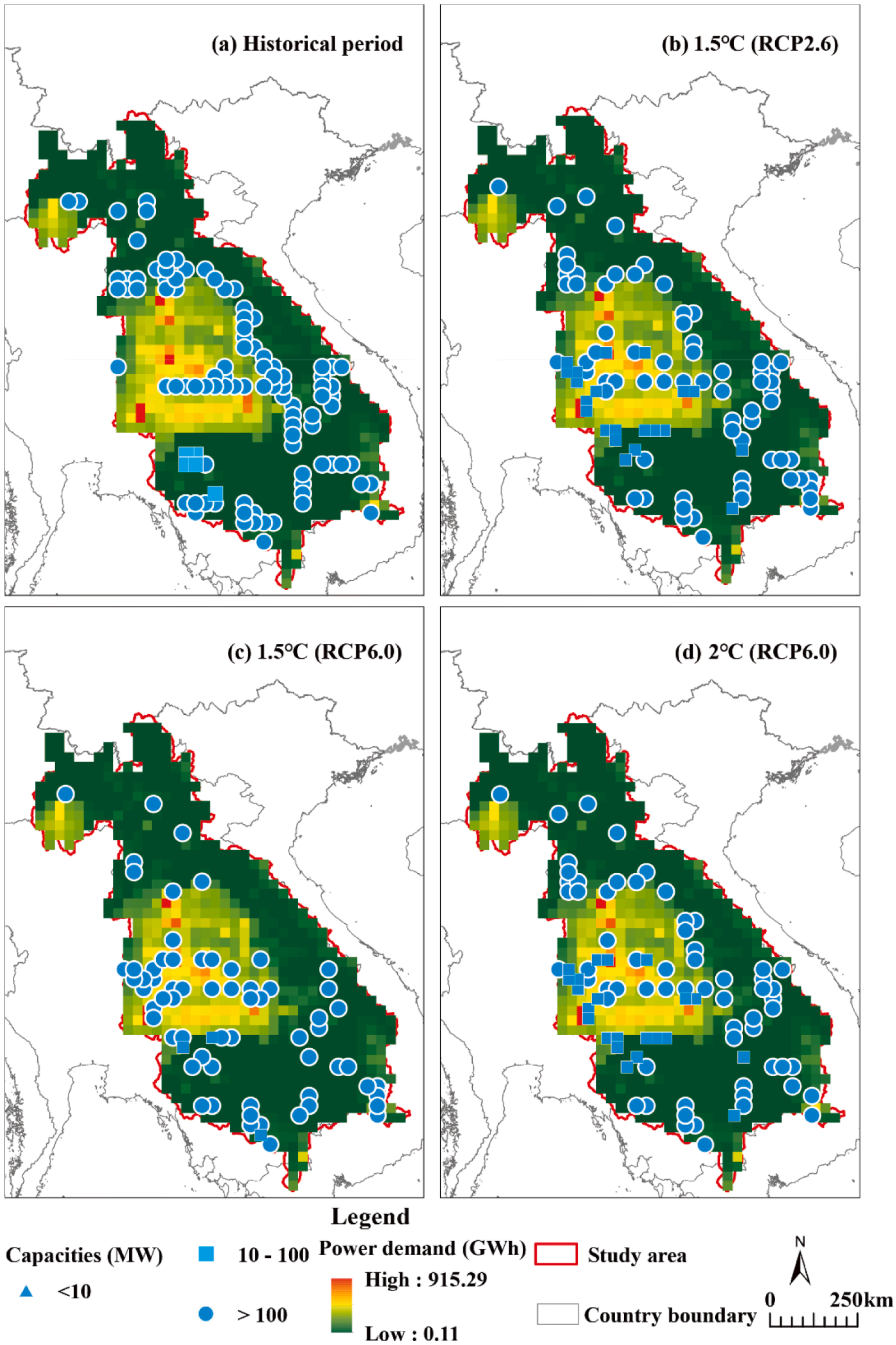

Fig. 4. Sites of hydropower plants under different scenarios of global warming in the study area.

2.3. Identifications of the hydropower-irrigation relation

Global warming could significantly influence the water supply and demand for hydropower and irrigation, which in turn will affect the complementary relation between hydropower and irrigation. In our study, potential irrigation water for rice was estimated by considering potential evapotranspiration (Williams et al., 1989; Liu et al., 2007) which is largely affected by climate factors (Wang and Zhao, 2011) under different global warming scenarios. Furthermore, hydropower production can also be effected by global warming due to the reason that global warming may affect the availability and steadiness of water resources (Arnell and Gosling, 2013; Zeng et al., 2017).

The dam construction for hydropower could benefit irrigation by discharge regulation, especially in the dry season. In the Mekong River basin, there is a positive synergy relationship (the complementary relationship) between hydropower generation and irrigation supply (Zeng et al., 2017). Here, we use the ratio of change in the irrigation water supply versus the change in the hydropower production to measure the intensity of changes in hydropower-irrigation relation. The intensity of the change of the hydropower-irrigation relation is less undermined when the ratio of change in the irrigation water supply versus the change in the hydropower production is closer to 1:1.

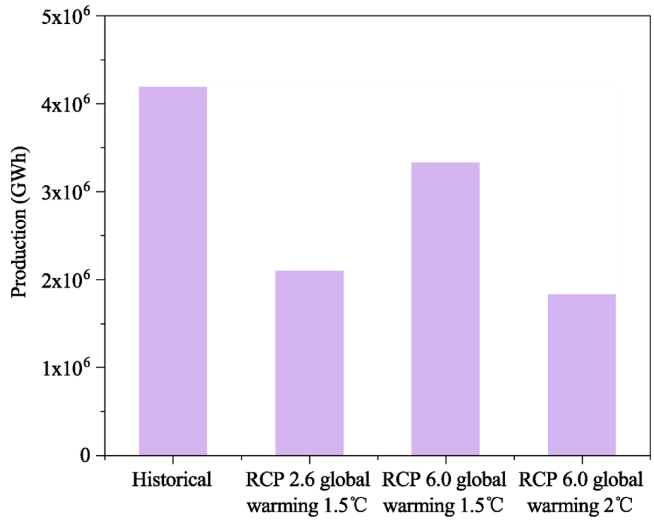

Fig. 5. Hydropower production at the historical period and different scenarios of global warming.

3. Results and discussion

3.1. Generation of potential hydropower plants

The gross hydropower potential in Mekong River basin is 3069 MW, 2936 MW, 2677 MW and 2791 MW respectively under the historical period, the scenario of 1.5 °C (RCP2.6), 1.5 °C (RCP6.0) and 2 °C (RCP6.0), for the whole Mekong River basin. The gross hydropower potential is larger under the scenario of 2 °C (RCP6.0) than 1.5 °C (RCP6.0) although the gross hydropower potential under both scenarios of global warming is smaller than that in the historical period. Fig. 3 shows the gross hydropower potential distribution during the historical period, and the differences between the historical period and the 1.5 °C and 2 °C global warming scenarios. Most areas in the Mekong River basin show decreasing trends of the hydropower potential under 1.5 °C and 2 °C global warming scenario especially in the grids around the mainstream. The highest hydropower potential during the historical period locates along the Mekong River mainstream where the hydropower potential reduces most under the global warming scenarios.

Locations suitable for setting up hydropower plants under different scenarios simulated by the BeWhere model are shown in Fig. 4. The shape of blue circles (Fig. 4) represents the different capacities of hydropower plants. The sites of hydropower plants are concentrated in the downstream region of the Mekong River basin (Thailand and Cambodia) where the demand of electricity is larger because of the high population density and irrigation development (FAO, 2011; Pech and Sunada, 2008). The size of plants under the 1.5 °C global warming is larger in the western part of the Mekong River basin than the global warming of 2 °C. This finding reveals that a higher number of hydropower plants are needed to meet the electricity demand under the 2 °C global warming than the 1.5 °C scenario. However, the total hydropower generation under the 2 °C global warming is still less than that under the 1.5 °C global warming (Fig. 5).

Fig. 5 shows the hydropower generation under different scenarios of global warming in Mekong River basin. For the whole study area, the total production provided by the potential hydropower plants is 4.19×10^6 GWh, 2.10×10^6 GWh, 3.33×10^6 GWh and 1.84×10^6 GWh under the historical period, the scenarios of 1.5 °C (RCP2.6), 1.5 °C (RCP6.0) and 2 °C (RCP6.0). The hydropower generation under 2 °C (RCP6.0) is less than both scenarios of 1.5 °C (RCP2.6) and 1.5 °C (RCP6.0), which is not consistent with the trend of the gross hydropower potential under 2 °C (RCP6.0) and 1.5 °C (RCP6.0). The gross hydropower potential is larger under 2 °C (RCP6.0) than 1.5 °C (RCP6.0). The inconformity arises from considering the economic factors except the hydropower potential when selecting hydropower plants. Thus, the hydropower generation showed an incongruous change with gross hydropower potential under 2 °C (RCP6.0) than 1.5 °C (RCP6.0). The hydropower generation decreases by 49.82%, 20.48% and 56.21% under the scenarios of 1.5 °C (RCP2.6), 1.5 °C (RCP6.0) and 2 °C (RCP6.0), separately, compared to the historical period. The results reveal that increasing global warming levels decrease hydropower production.

3.2. Irrigation water supply for rice

The distribution of the simulated historical irrigation water supply for rice and the changes of the irrigation water supply for rice under the 1.5 °C and 2 °C global warming scenarios referred to the historical period are shown in Fig. 6. A high irrigation water supply for rice is distributed at the outlet of the Mekong River basin during the historical period. A decreasing trend of irrigation water supply for rice comes up in large parts of the Mekong River basin under the scenarios of 1.5 °C (RCP2.6), 1.5 °C (RCP6.0) and 2 °C (RCP6.0) compared to the historical period (shown in Fig. 6(b), (c), (d)). The area with a decreasing trend of irrigation water supply for rice under the 1.5 °C (RCP6.0) is less than that in the scenarios of 1.5 °C (RCP2.6) and 2 °C (RCP6.0). The distribution of the maximum value of the decreasing is concentrated along the mainstream under the global warming scenario (Fig. 6(b), (c), (d)). For the whole study area, the mean value of irrigation water supply for rice decreases 30.98 mm, 26.99 mm and 40.63 mm under the scenarios of 1.5 °C (RCP2.6), 1.5 °C (RCP6.0) and 2 °C (RCP6.0), respectively. The irrigation water supply decreases by 20.10%, 17.51% and 26.36% under the scenarios of 1.5 °C (RCP2.6), 1.5 °C (RCP6.0) and 2 °C (RCP6.0) compared to the historical period. The consequence shows a consistent trend (decreasing) with hydropower production in the Mekong River basin compared to the historical period.

3.3. Global warming effects on the hydropower-irrigation relation

The total hydropower production decreases by 49.82%, 20.48% and 56.21% under the scenarios of 1.5 °C (RCP2.6), 1.5 °C (RCP6.0) and 2 °C (RCP6.0) compared to the historical period. The irrigation water supply decreases by 20.10%, 17.51% and 26.36% under scenarios of the 1.5 °C (RCP2.6), 1.5 °C (RCP6.0) and 2 °C (RCP6.0) compared to the historical period. Both decreasing trends are consistent with the trend of discharge in the Mekong River basin (shown in Figure S3). And both decreasing trends indicate the negative influences of global warming on the hydropower generation and irrigation supply. And the correlation between hydropower generation and irrigation is still positive. In addition, the hydropower production decreases by 35.73% from 1.5 °C (RCP6.0) to 2 °C (RCP6.0) but the irrigation water supply decreases by 8.85% from 1.5 °C (RCP6.0) to 2 °C (RCP6.0). The different percentages indicate that the decreasing trend of the irrigation water supply is slower than that of hydropower production. It implies that the hydropower generation is much more undermined by the global warming of 2 °C than irrigation water supply. Furthermore, the ratio of irrigation water supply versus hydropower production decreases from 6:7 under 1.5 °C (RCP6.0) to 1:2 under 2 °C (RCP6.0) (Table 1). It indicates the complementary between hydropower generation and irrigation supply is undermined by the global warming of 2 °C relative to global warming of 1.5 °C.

3.4. Effects of conserving protected land on the hydropower-irrigation relation under global warming

All locations provided by BeWhere are presented in Figure S4. However, a part of the hydropower plants is located at the protected areas (including natural protected forests and national parks) since the results from the BeWhere model only consider the economic factors but do not account for the environmental impacts. Therefore, we removed

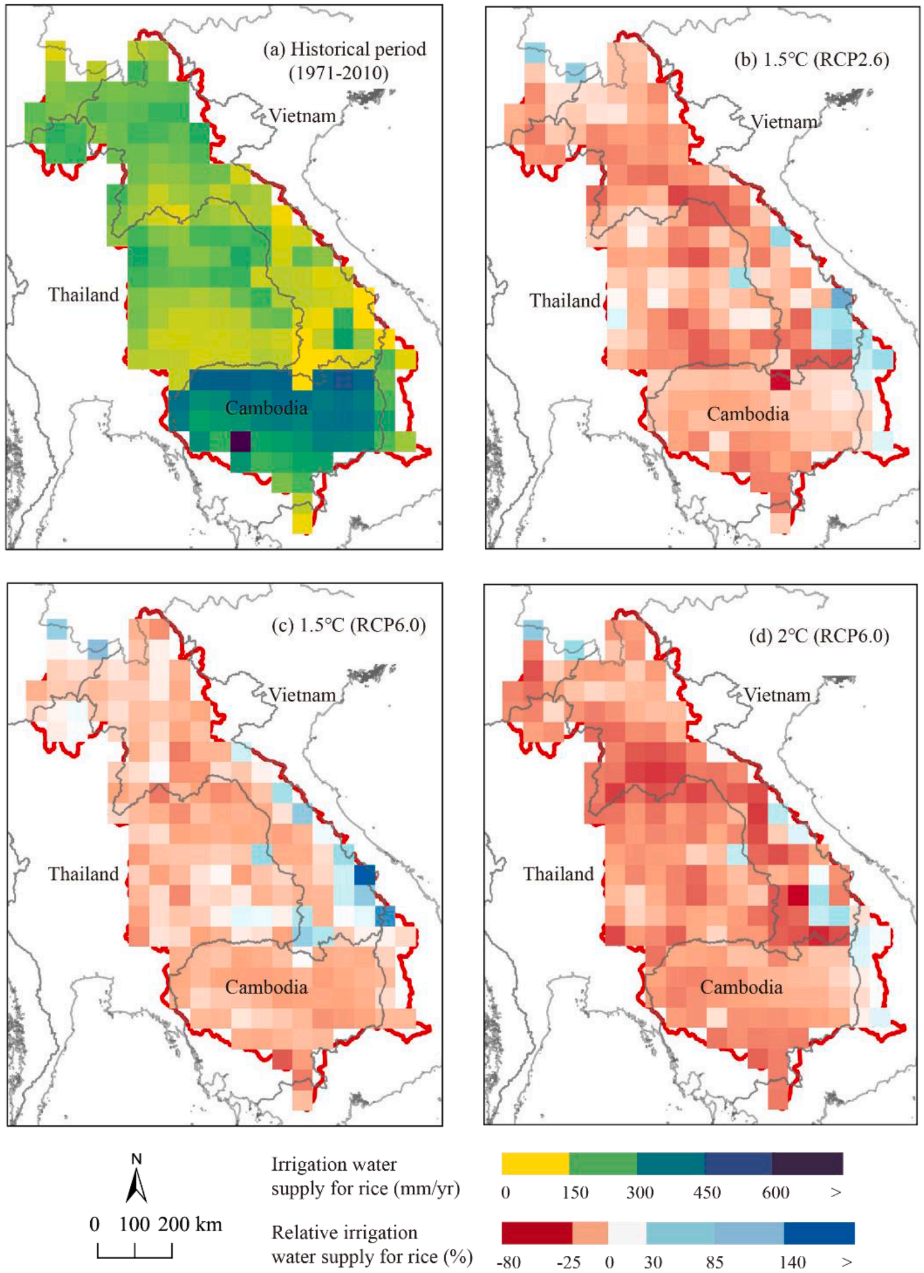

Fig. 6. Annual mean irrigation water supply for rice (mm per growing season) (1970–2010), and the differences in the annual mean irrigation water supply for rice between historical period and the global warming scenarios of 1.5 °C and 2 °C.

the sites at the protected areas manually in Fig. 7 and Figure S5. Although the number of the hydropower plants drop significantly after excluding the sites located at the protected areas (compared to Fig. 4), the sites of the hydropower plants are still concentrated in the downstream of the Mekong River basin (Thailand and Cambodia).

For the whole study area, the total hydropower generation will be 9.69×10^5 GWh, 1.32×10^6 GWh, 9.39×10^5 GWh and 6.85×10^5 GWh when excluding sites located at the protected areas under the historical period, the scenarios of 1.5 °C (RCP2.6), 1.5 °C (RCP6.0) and 2 °C (RCP6.0) (Fig. 8). It suggests that the total production will decrease by 37% ~ 77% when considering the effects of protected areas compared to the original simulated results by BeWhere. Furthermore, the total production when excluding the protected areas decreases by 3.05% and 29.34% under 1.5 °C (RCP6.0) and 2 °C (RCP6.0) but increases by 36.66% under 1.5 °C (RCP2.6) scenarios compared to the historical period (Table 2). The incongruous trend (an increasing trend of hydropower generation when excluding protected areas and a decreasing trend of irrigation water supply under 1.5 °C (RCP2.6) scenarios) indicates that the relationship between hydropower generation and irrigation water supply converts to competition from complementary. Moreover, the ratio of irrigation water supply versus hydropower production when considering the protected areas is 23:4 and 8:9 under the scenarios of 1.5 °C (RCP6.0) and 2 °C (RCP6.0) (shown in Table 2). It implies the complementary is enhanced from the global warming of 1.5 °C to 2 °C under RCP 6.0 when considering the effects of protected areas. However, the complementary between hydropower generation and irrigation supply is undermined from global warming of 1.5 °C (6:7) to 2 °C (1:2) under RCP 6.0 (shown in Table 1). Notably, the relationship between hydropower production and irrigation water supply is reversed when considering the protected areas.

Table 1
The variations in hydropower production and irrigation water supply under different scenarios of global warming compared to the historical period.

Global warming scenarios	Hydropower production (%)	Irrigation water supply in rice (%)	Irrigation versus hydropower
[1]1.5 °C (RCP2.6) - Historical period	−49.82	−20.10	2:5
[2]1.5 °C (RCP6.0) - Historical period	−20.48	−17.51	6:7
[3]2 °C (RCP6.0) - Historical period	−56.21	−26.36	1:2
[4]2 °C (RCP6.0) - 1.5 °C (RCP6.0)	−35.75	−8.85	1:4

[1] the difference between 1.5 °C (RCP2.6) and Historical period;.
[2] the difference between 1.5 °C (RCP6.0) and Historical period;.
[3] the difference between 2 °C (RCP6.0) and Historical period;.
[4] the difference between the scenario of 2 °C (RCP6.0) and 1.5 °C (RCP6.0).

3.5. Limitations and perspectives for future research

Investigating global warming scenarios effects on hydropower and irrigation in this work mainly considers the climate effects. The simulated results are based on the global hydrological model and crop model at a ~50 km × 50 km resolution. A higher spatial resolution in further work could help to improve the accuracy of the results (Bell et al., 2018). In our study, we chose the individual years to represent the global warming of 1.5 and 2 °C and a multi-year mean around those years would be more representative. Moreover, the simulated discharge is only from one global hydrological model. Further research will consider multiple hydrological models to reduce the uncertainties of model simulation (Scanlon et al., 2018). Pokhrel et al. (2018) estimated that the hydropower potential of the mainstem Mekong is ~53,000 MW with another ~35,000 MW from tributaries. It is bigger than our result (3069 MW during the Historical period). It is because the study area in Pokhrel et al. (2018) is the entire Lancang-Mekong River basin, i.e., including more mountainous Lancan basin with significant rainfall. However, in the Mekong River basin, the elevation difference is smaller than the Lancang River basin. Therefore, the estimation of the hydropower potential is smaller than that in Pokhrel et al. (2018).

We did not consider the limit of reservoir storage on the irrigation water supply in our study because of data limitation. The simulated data for discharge and irrigation water supply for rice are provided by two separate models, i.e., PCR-GLOBWB and GEPIC. The data could be more consistent if we could use a coupled model integrating hydrological and crop elements to determine the relation between discharge and evapotranspiration. The irrigation efficiency (*Ei*) was set to 0.4 for the entire study area and time period (Döll and Siebert, 2002). If the irrigation efficiency (*Ei*) would change under the climate change, the amount of water demand for irrigation would also change. Furthermore, the irrigation water supply could be overestimated as we assumed it equals to the water demand. The BeWhere model is constrained by power consumption and we did not consider other services of the hydropower dams, such as flood control and urban water supply, which could underestimate the benefits brought by reservoirs construction. Considering more functions of reservoirs in further work could replenish comprehensiveness of tradeoffs of dams for decision-makers (Singh, 2015). In addition, we assumed that the electricity demand was consistent in the BeWhere model because we would like to focus on the global warming effects on the hydropower generation, which could undermine the hydropower generation in the future.

The relationship between hydropower and irrigation in this study only considered surface water. However, groundwater is also used for irrigation in Vietnam (Pokhrel et al., 2018a), and the groundwater extraction for irrigation could indirectly impact the hydropower production through the groundwater and surface water interaction (Velis et al., 2017). It is estimated that the area irrigated by groundwater currently accounts for 2% of the total irrigated areas (FAO, 2011). There is far less groundwater utilization for irrigation in the Mekong River basin relative to other agricultural areas around the world (Aeschbach-Hertig and Gleeson, 2012), but there has been an increasing trend of using groundwater for irrigation in the region (Pokhrel et al., 2018a). Thus, it is crucial to consider groundwater pumping effects on irrigation in coming studies because it could change the relationship between hydropower and irrigation from complementary to competition.

5. Conclusions

This study assessed the effects of the 1.5 °C and 2 °C global warming on the co-benefits between hydropower generation and irrigation water supply in the Mekong River basin by an integrative analysis framework based on the hydrological, techno-economic and agricultural model chain. We found that the hydropower generation and irrigation water supply in the Mekong River basin are projected to decrease under both scenarios. Moreover, the co-benefits between the hydropower production and the irrigation water supply in the Mekong River basin is more undermined by the 2 °C warming relative to 1.5 °C warming. However, the relationship is reversed when considering the protected areas in the basin. The complementary between hydropower (excluding sites located at the protected areas) and irrigation is enhanced when comparing 2 °C warming with 1.5 °C warming. The relationship even becomes competing when considering the protected areas under RCP 2.6–1.5 °C. Therefore, decision-makers should pay more attention to the tradeoff between conserving protected area and the dam constructions for ensuring energy and food security.Our research synthetically investigated the influences of global warming scenarios on the relationship between hydropower generation and irrigation supply. Moreover, we simulate the optimal locations of hydropower dams in the Mekong River basin under global warming scenarios of 1.5 °C and 2 °C. The results would provide scientific support for decision-makers to secure regional energy and food supply under climate change.

Credit author statement

YING MENG: Data collection; Methodology; Formal analysis; Investigation.
JUNGUO LIU: Supervision; Review and editing
ZIFENG WANG: Data collection; Formal analysis; Methodology; Review and editing
GANQUAN MAO: Methodology; Review and editing
KAI WANG: Data collection; Review and editing
HONG YANG: Review and editing

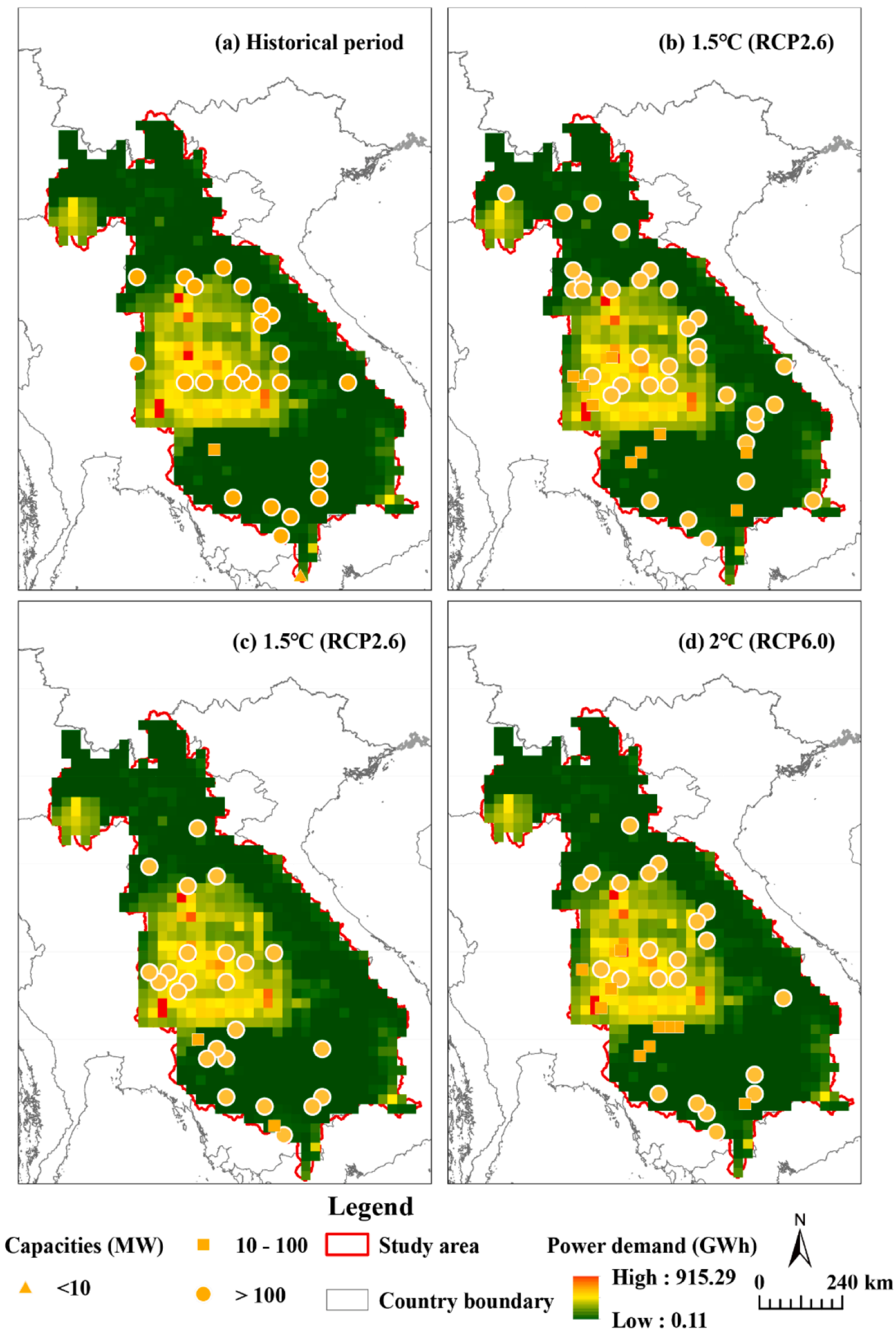

Fig. 7. Optimal locations for plants by excluding hydropower plants located at protected areas under different scenarios of global warming.

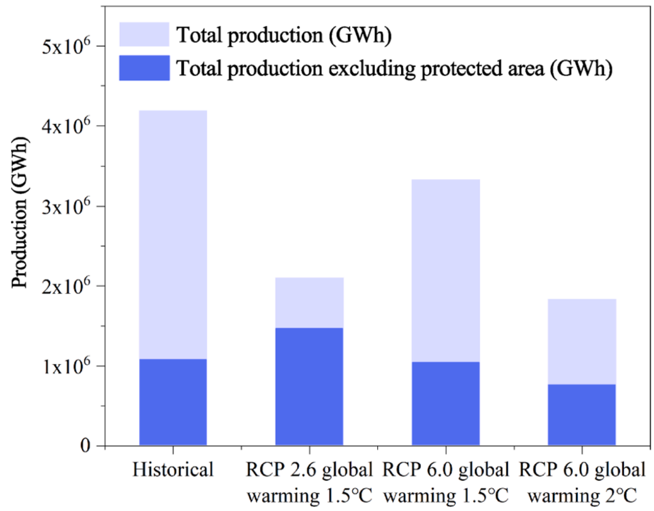

Fig. 8. Hydropower production excluding the sites at protected areas under the historical period and different global warming scenarios.

Table 2
The variations in hydropower production considering the protected areas and irrigation water supply under global warming scenarios of 1.5 °C and 2 °C compared to the historical period.

Global warming scenarios	Hydropower production by considering protected areas (%)	Irrigation water supply in rice (%)	Irrigation versus hydropower
[1]1.5 °C (RCP2.6) - Historical period	36.66	−20.10	−5:9
[2]1.5 °C (RCP6.0) - Historical period	−3.05	−17.51	23:4
[3]2 °C (RCP6.0) - Historical period	−29.34	−26.36	8:9
[4]2 °C (RCP6.0) - 1.5 °C (RCP6.0)	−26.39	−8.85	1:3

[1] the difference between 1.5 °C (RCP2.6) and Historical period;.
[2] the difference between 1.5 °C (RCP6.0) and Historical period;.
[3] the difference between 2 °C (RCP6.0) and Historical period;.
[4] the difference between the scenarios of 2 °C (RCP6.0) and 1.5 °C (RCP6.0).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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The discharge and irrigation data provided by the ISIMIP could be found from https://www.isimip.org/. The data of hub distribution is from OpenStreetMap and available from https://www.openstreetmap.org

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2020.105375.

References

Aeschbach-Hertig, W., Gleeson, T., 2012. Regional strategies for the accelerating global problem of groundwater depletion. Nat. Geosci. 5, 853–861. https://doi.org/10.1038/ngeo1617.
Almeida, R.M., Shi, Q., Gomes-Selman, J.M., Wu, X., Xue, Y., Angarita, H., Barros, N., Forsberg, B.R., García-Villacorta, R., Hamilton, S.K., Melack, J.M., Montoya, M., Perez, G., Sethi, S.A., Gomes, C.P., Flecker, A.S., 2019. Reducing greenhouse gas emissions of Amazon hydropower with strategic dam planning. Nat. Commun. 10, 1–9. https://doi.org/10.1038/s41467-019-12179-5.
Arnell, N.W., Gosling, S.N., 2013. The impacts of climate change on river flow regimes at the global scale. J. Hydrol. 486, 351–364. https://doi.org/10.1016/j.jhydrol.2013.02.010.
Bell, R.E., Banwell, A.F., Trusel, L.D., Kingslake, J., 2018. Antarctic surface hydrology and impacts on ice-sheet mass balance. Nat. Clim. Chang. 8. https://doi.org/10.1038/s41558-018-0326-3.
Bergendahl, J.A., Sarkis, J., Timko, M.T., 2018. Transdisciplinarity and the food energy and water nexus: ecological modernization and supply chain sustainability perspectives. Resour. Conserv. Recycl. 133, 309–319. https://doi.org/10.1016/j.resconrec.2018.01.001.
Black & Veatch, 2012. Cost and Performance Data For Power Generation Technolo- gies.
Döll, P., Siebert, S., 2002. Global modeling of irrigation water requirements. Water Resour. Res. 38 https://doi.org/10.1029/2001wr000355, 8-1-8–10.
FAO, 2011. AQUASTAT Transboundary River Basins – Mekong River Basin. Rome, Italy.
FAO, 1997. Irrigation Potential in Africa: A basin Approach.
FAO, 2020. AQUASTAT Core Database. n.d.. Food and Agriculture Organization of the United Nations [WWW Document]URL. http://www.fao.org/aquastat/en/databases/maindatabase/. accessed 10.28.20.
Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., Kolp, P., Strubegger, M., Valin, H., Amann, M., Ermolieva, T., Forsell, N., Herrero, M., Heyes, C., Kindermann, G., Krey, V., McCollum, D.L., Obersteiner, M., Pachauri, S., Rao, S., Schmid, E., Schoepp, W., Riahi, K., 2017. The marker quantification of the Shared Socioeconomic Pathway 2: a middle-of-the-road scenario for the 21st century. Glob. Environ. Chang. 42, 251–267. https://doi.org/10.1016/j.gloenvcha.2016.06.004.
Frieler, K., Lange, S., Piontek, F., Reyer, C.P.O., Schewe, J., Warszawski, L., Zhao, F., Chini, L., Denvil, S., Emanuel, K., Geiger, T., Halladay, K., Hurtt, G., Mengel, M., Murakami, D., Ostberg, S., Popp, A., Riva, R., Stevanovic, M., Ts, T.S., Volkholz, J., Burke, E., Ciais, P., Ebi, K., 2017. Assessing the impacts of 1 . 5 ° C global warming – simulation protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b). Geosci. Model Dev. 10, 4321–4345. https://doi.org/10.5194/gmd-10-4321-2017.
Hoang, L.P., van Vliet, M.T.H., Kummu, M., Lauri, H., Koponen, J., Supit, I., Leemans, R., Kabat, P., Ludwig, F., 2019. The Mekong's future flows under multiple drivers: how climate change, hydropower developments and irrigation expansions drive hydrological changes. Sci. Total Environ. 649, 601–609. https://doi.org/10.1016/j.scitotenv.2018.08.160.
Williams, J.R., Jones, C.A., Kiniry, J.R., Spanel, D.A., 1989. The EPIC Crop Growth Model. Trans. ASAE 32. https://doi.org/10.13031/2013.31032, 0497–0511.
Latrubesse, E.M., Arima, E.Y., Dunne, T., Park, E., Baker, V.R., D'Horta, F.M., Wight, C., Wittmann, F., Zuanon, J., Baker, P.A., Ribas, C.C., Norgaard, R.B., Filizola, N., Ansar, A., Flyvbjerg, B., Stevaux, J.C., 2017. Damming the rivers of the Amazon basin. Nature. https://doi.org/10.1038/nature22333.
Leduc, S., Lundgren, J., Franklin, O., Dotzauer, E., 2010. Location of a biomass based methanol production plant: a dynamic problem in northern Sweden. Appl. Energy. https://doi.org/10.1016/j.apenergy.2009.02.009.
Leduc, S., Schwab, D., Dotzauer, E., Schmid, E., Obersteiner, M., 2008. Optimal location of wood gasification plants for methanol production with heat recovery. Int. J. Energy Res. 32, 1080–1091. https://doi.org/10.1002/er.1446.
Lehner, B., Verdin, K., Jarvis, A., 2008. New global hydrography derived from spaceborne elevation data. Eos (Washington. DC) 89, 93–94. https://doi.org/10.1029/2008EO100001.
Liu, J., Williams, J.R., Zehnder, A.J.B., Yang, H., 2007. GEPIC - modelling wheat yield and crop water productivity with high resolution on a global scale. Agric. Syst. 94, 478–493. https://doi.org/10.1016/j.agsy.2006.11.019.
Liu, J., Yang, H., Cudennec, C., Gain, A.K., Hoff, H., Lawford, R., Qi, J., Strasser, L., de Yillia, P.T., Zheng, C., 2017. Challenges in operationalizing the water–energy–food nexus. Hydrol. Sci. J. 62, 1714–1720. https://doi.org/10.1080/02626667.2017.1353695.
Maavara, T., Chen, Q., Van Meter, K., Brown, L.E., Zhang, J., Ni, J., Zarfl, C., 2020. River dam impacts on biogeochemical cycling. Nat. Rev. Earth Environ. 1, 103–116. https://doi.org/10.1038/s43017-019-0019-0.

Meng, Y., Liu, J., Leduc, S., Mesfun, S., Kraxner, F., Mao, G., Qi, W., Wang, Z., 2020. Hydropower production benefits more from 1.5°C than 2°C climate scenario. Water Resour. Res. https://doi.org/10.1029/2019WR025519, 2019WR025519.
Mesfun, S., Leduc, S., Patrizio, P., Wetterlund, E., Mendoza-Ponce, A., Lammens, T., Staritsky, I., Elbersen, B., Lundgren, J., Kraxner, F., 2018. Spatio-temporal assessment of integrating intermittent electricity in the EU and Western Balkans power sector under ambitious CO2emission policies. Energy 164, 676–693. https://doi.org/10.1016/j.energy.2018.09.034.
Mesfun, S., Sanchez, D.L., Leduc, S., Wetterlund, E., Lundgren, J., Biberacher, M., Kraxner, F., 2017. Power-to-gas and power-to-liquid for managing renewable electricity intermittency in the Alpine Region. Renew. Energy 107, 361–372. https://doi.org/10.1016/j.renene.2017.02.020.
MRC, 2011. Mekong River Commission Basin Development Plan Programme, Phase 2 Working Towards an IWRM-Based Basin Development Strategy for the Lower Mekong Basin.
MRC, 2010. Mekong River Commission, State of the Basin Report 2010. Summary.
OpenStreetMap, 2015. Planet Dump retrieved from. https://planet.osm.org.
Ove, Hoegh-Guldberg, Jacob, D., Taylor, M., et al., 2018. Impacts of 1.5°C global warming on natural and human systems. Glob. Warm. 1.5°C - IPCC's Spec. Assess. Rep. https://doi.org/10.1093/aje/kwp410.
Owusu, P.A., Asumadu-Sarkodie, S., 2016. A review of renewable energy sources, sustainability issues and climate change mitigation. Cogent Eng 3, 1–14. https://doi.org/10.1080/23311916.2016.1167990.
Pech, S., Sunada, K., 2008. Population growth and natural-resources pressures in the mekong river Basin. https://doi.org/10.1579/0044-7447(2008)37[219:PGANPI]2.0.CO;2 37, 219–224. https://doi.org/10.1579/0044-7447(2008)37[219:PGANPI]2.0.CO;2.
Pokhrel, Y., Burbano, M., Roush, J., Kang, H., Sridhar, V., Hyndman, D., 2018a. A review of the integrated effects of changing climate, land use, and dams on Mekong River Hydrology. Water (Basel) 10, 266. https://doi.org/10.3390/w10030266.
Pokhrel, Y., Shin, S., Lin, Z., Yamazaki, D., Qi, J., 2018b. Potential disruption of flood dynamics in the Lower Mekong River basin due to upstream flow regulation. Sci. Rep. 8 https://doi.org/10.1038/s41598-018-35823-4.
Scanlon, B.R., Zhang, Z., Save, H., Sun, A.Y., Müller Schmied, H., van Beek, L.P.H., Wiese, D.N., Wada, Y., Long, D., Reedy, R.C., Longuevergne, L., Döll, P., Bierkens, M.F.P., 2018. Global models underestimate large decadal declining and rising water storage trends relative to GRACE satellite data. Proc. Natl. Acad. Sci. https://doi.org/10.1073/pnas.1704665115, 201704665.
Shi, C., Jiang, Z.-H., Chen, W.-L., Li, L., 2018. Changes in temperature extremes over China under 1.5°C and 2°C global warming targets. Adv. Clim. Chang. Res. 9, 120–129. https://doi.org/10.1016/J.ACCRE.2017.11.003.
Singh, V., 2015. An overview of hydro-electric power plant. J. Mech. Eng. 6, 59–62.
Sunday, J.M., 2020. The pace of biodiversity change in a warming climate. Nature 580, 460–461. https://doi.org/10.1038/d41586-020-00975-9.
Sutanudjaja, E.H., Van Beek, R., Wanders, N., Wada, Y., Bosmans, J.H.C., Drost, N., Van Der Ent, R.J., De Graaf, I.E.M., Hoch, J.M., De Jong, K., Karssenberg, D., López López, P., Peßenteiner, S., Schmitz, O., Straatsma, M.W., Vannametee, E., Wisser, D., Bierkens, M.F.P., 2018. PCR-GLOBWB 2: a 5 arcmin global hydrological and water resources model. Geosci. Model Dev. 11, 2429–2453. https://doi.org/10.5194/gmd-11-2429-2018.
Tobin, I., Greuell, W., Jerez, S., Ludwig, F., Vautard, R., van Vliet, M.T.H., Bréon, F.-.M., 2018. Vulnerabilities and resilience of European power generation to 1.5°C, 2°C and 3°C warming. Environ. Res. Lett. 13, 044024 https://doi.org/10.1088/1748-9326/aab211.
United Nations Framework Convention on Climate Change [UNFCCC], 2015. Paris Agreement. Paris Agreem. 25. https://doi.org/FCCC/CP/2015/L.9.
van Vliet, M.T.H., Wiberg, D., Leduc, S., Riahi, K., 2016. Power-generation system vulnerability and adaptation to changes in climate and water resources. Nat. Clim. Chang. 6, 375–380. https://doi.org/10.1038/nclimate2903.
van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-.F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K., 2011. The representative concentration pathways: an overview. Clim. Change 109, 5–31. https://doi.org/10.1007/s10584-011-0148-z.
Velis, M., Conti, K.I., Biermann, F., 2017. Groundwater and human development: synergies and trade-offs within the context of the sustainable development goals. Sustain. Sci. 12, 1007–1017. https://doi.org/10.1007/s11625-017-0490-9.
Wada, Y., Wisser, D., Bierkens, M.F.P., 2014. Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources. Earth Syst. Dyn. 15–40. https://doi.org/10.5194/esd-5-15-2014.
Waldman, J., Sharma, S., Afshari, S., Fekete, B., 2019. Solar-power replacement as a solution for hydropower foregone in US dam removals. Nat. Sustain. 2, 872–878. https://doi.org/10.1038/s41893-019-0362-7.
Wang, X., Zhao, C., 2011. Analysis of temporal trends in potential evaportranspiration over Heihe River basin. In: ISWREP 2011 - Proceedings of 2011 International Symposium on Water Resource and Environmental Protection, pp. 806–809. https://doi.org/10.1109/ISWREP.2011.5893130.
Zarfl, C., Berlekamp, J., He, F., Jähnig, S.C., Darwall, W., Tockner, K., 2019. Future large hydropower dams impact global freshwater megafauna. Sci. Rep. 9, 1–10. https://doi.org/10.1038/s41598-019-54980-8.
Zeng, R., Cai, X., Ringler, C., Zhu, T., 2017. Hydropower versus irrigation—An analysis of global patterns. Environ. Res. Lett. 12, 034006 https://doi.org/10.1088/1748-9326/aa5f3f.
Zewdie, M.C., Van Passel, S., Cools, J., Tenessa, D.B., Ayele, Z.A., Tsegaye, E.A., Minale, A.S., Nyssen, J., 2019. Direct and indirect effect of irrigation water availability on crop revenue in northwest Ethiopia: a structural equation model. Agric. Water Manag. 220, 27–35. https://doi.org/10.1016/j.agwat.2019.04.013.
Zhang, X., Li, H.Y., Deng, Z.D., Ringler, C., Gao, Y., Hejazi, M.I., Leung, L.R., 2018. Impacts of climate change, policy and Water-Energy-Food nexus on hydropower development. Renew. Energy. https://doi.org/10.1016/j.renene.2017.10.030.
Zhang, Y., Gu, A., Lu, H., Wang, W., 2017. Hydropower generation vulnerability in the Yangtze River in China under climate change scenarios: analysis based on the WEAP model. Sustainability 9, 2085. https://doi.org/10.3390/su9112085.
Zhou, Y., Hejazi, M., Smith, S., Edmonds, J., Li, H., Clarke, L., Calvin, K., Thomson, A., 2015. A comprehensive view of global potential for hydro-generated electricity. Energy Environ. Sci. 8, 2622–2633. https://doi.org/10.1039/c5ee00888c.