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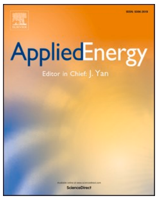

Water and carbon risks within hydropower development on national scale

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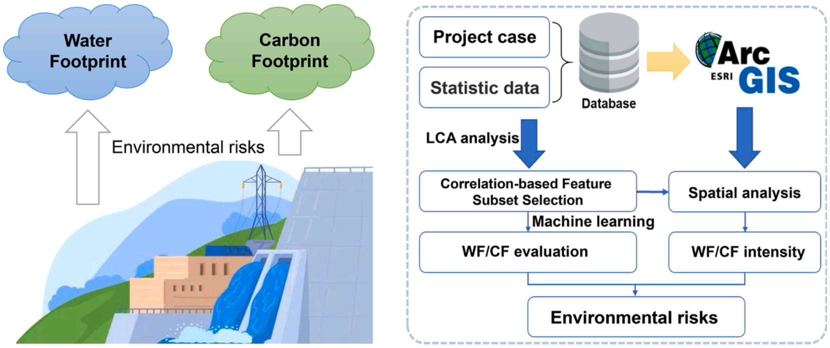
HIGHLIGHTS

- The positive and negative environmental benefits of hydropower are co-existed, and it cannot be ignored.
- This study firstly assessed environmental burden at national scale, including water footprint and carbon footprint.
- Machine learning offers a new approach: estimating environmental burden of hydropower with inadequate data.
- Hydropower replacing thermal power cannot achieve complete cleanliness.

GRAPHICAL ABSTRACT



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ABSTRACT

The United Nations has proposed Sustainable Development Goals (SDGs), which aim to achieve coordinated green development in energy, economic and environmental dimensions. Hydropower is currently the world's most important renewable energy source, it has made up for the electricity shortage and created great economic value, but at the same time, the environmental impacts occurred cannot be ignored. However, current studies focused on a single or a few specific projects, it has not achieved quantitative environmental assessment on regional scale. To fill this gap, we selected China, the world's largest developing country, as the case for the first time to assess the hydropower water footprint (WF) and carbon footprint (CF) at both spatial and temporal dimensions. The results showed that total WF & CF of hydropower in China are 13.90 billion m^3 (closes to half annually runoff of the Yellow River) and 413.39 billion kg $eqCO_2$ (is equivalent to burning 1.5 billion t of coal), with intensity of 53.95 m^3/MWh and 125.89 kg $eqCO_2$/MWh respectively. The hydropower WF alone is more than regional available water occurred in 1/4 provinces of China. The emission reduction effect of hydropower is overestimated by 11.72 %, this should be considered in plans that hydropower replacing thermal power.

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Considering the CF of hydropower itself, 25–53 % of the regional carbon emission reduction target would not be achieved. From a global perspective, there about 1/3 countries' hydropower WF exceed 10 % of the water resource availability, and about 1/4 countries' hydropower CF exceeds 5 % of carbon emission.

1. Introduction

Hydropower is currently the largest source of renewable electricity over world [1], and is widely regarded as a clean and environmental friendly energy source [2]. Hydropower brings electricity and industry, thereby developing the economy [3], expanding access to health and education, improving human-being, and ultimately promoting Sustainable Development Goals (SDGs) [4,5]. But, due to its environmental risks (e.g. resources consumption, indirect carbon emissions and etc.) [6], take comprehensive assessment of the benefits and risks of hydropower is particularly important for achieving SDGs(e.g. SDG 6, SDG7 and SDG13).

Hydropower plants could supply safe and reliable electric to meet energy requirements from human survival and economic development [7]. Until 2021, the global hydroelectric installed capacity reached 1340 GW, and which is expected to produce 4306 TWh of clean power [8]. Hydropower generates 15.6 % of the global electricity, accounting for 2/3 of the total renewable energy power generation, which is capable to meet the global electricity consumption of 1/7 of the population [8]. China's hydroelectric generation amounted to 1302 TWh and accounting for approximately30.2 % of the global total hydroelectric capacity in 2021. Hydropower development has produced huge direct economic benefits, solved regional energy shortage, and promoted the development of industrial and manufacturing industries, which has obviously promoted the economic and social progress. However, the continuous development of hydropower thereby leading to a considerable complex and diverse environmental risks, such as runoff change and ecological damage [9–11]. It is extremely difficult to strike a balance between maximizing the benefits of hydropower without raising environmental damages. Hence, accurately quantifying the impact of hydropower development on the environment is of great significance to achieve clean energy [12] and sustainability [13].

Hydropower development requires the construction of much hydropower plants, which consumed a large amount of resources (such as metal materials and energy input) and severely changed original surface runoff [14]. Greenhouse gas emissions and water consumption occurred in processes of construction and operation, which are directly or indirectly generated, are the two most important environmental burden of hydropower developments [15], evaluating GHG emissions and water consumption is very important for the sustainable development of hydropower. Water footprint (WF) [16,17] and carbon footprint (CF) [18] are considered to be the most common and useful methods quantifying the environmental impacts of hydropower environmental impacts [19]. Several researchers have considered the construction and operation phases and estimated the WF [20,21] and CF [22,23] of a single or multiple hydropower plants, such as in Brazil and China, which provided evidence of the feasibility of footprints method. Coelho et al [24] evaluated the CF of hydropower plants in China covered all construction stages, and analyzed its impact in flooded areas. Jiang et al [25] calculated the CF of four large-scaled hydroelectric plants in China and proposed emission reduction strategies. Some scholars analyzed WF and CF of hydropower plants in different countries, including Norway, Romania, and Brazil [24,26,27]. Wang et al [28] calculated WF and CF of 50 typical hydropower plants in China using Life Cycle Assessment (LCA) method, and clarified the boundaries and lists of WF and CF evaluation.

Based on the current state of this research field, there exists a requirement for evaluating the environmental risks of hydropower development on a regional scale. But due to the lack of construction data (e.g., raw materials and energy consumptions, etc.), only few hydropower plants with complete data can meet LCA principle and cannot cover all hydropower plants in a special region. The evaluation of a single station cannot reflect the regional problems and has obvious limitations on the regional hydropower development and management. Therefore, it is impossible to quantify the negative impacts of hydropower development on environment at regional scale accurately and provide theoretical support for water management and emission reduction.

This study chooses China as case study to take quantitative assessment of hydropower environmental risks, which is of great significance in promoting the achievement of sustainable development goals globally. The following three issues were intended to address: (1) explore hydropower water and carbon footprint and its spatial–temporal characteristics; (2) the impacts of hydropower development on regional water resources and carbon emissions reduction; (3) propose to reduce water and carbon footprints in hydropower development.

The rest of this study is organized as follows: Section 2 Materials and methods introduces the location of hydropower plants in China and methodologies and processes for calculating water and carbon risks at national scales, section 3 Results represents the temporal-spatial analysis of WF/CF and its impact factors, section 4 Discussion expounds the water stress and carbon stress at national scales and suggestions for hydropower sustainable development.

2. Materials and methods

2.1. Geographic distribution of hydropower plants in China

The natural conditions for developing hydropower are very potential in China (with hydropower reserves of 667 million kW China leads the world, China's Energy Policy, 2012). In recent years, the "13th Five-Years Developmental Plan" for hydropower and "National Hydropower Base Plan of China" have proposed to develop hydropower and reach to 1.47 trillion kWh in 2022 (National Energy Administration, EIA, 2019). This study involved 614 large and medium-sized hydropower plants in China (more than about 80 % of national total installed capacity). The annual hydropower generation accounted for 94 % of the total national hydropower generation and the total hydropower storage capacity accounted for 86.5 % of the national total.

In addition, the hydropower plants selected in this paper are distributed in 30 provinces across China. The density of hydropower plants in south-western provinces are relatively higher than northeast and northwest. According to the completeness of hydropower plant construction data, all plants were divided into two categories: Type I and Type II hydropower plants. The construction data of Type I hydropower plants (n = 50) is detailed enough for water and carbon footprints' LCA analysis while the construction data of Type II hydropower plants (n = 564) could not realize WF and CF evaluation by LCA method according to the data limitation. The geographical distribution hydropower plants are depicted in Fig. 1. The details descriptions of hydropower plants are listed in ***Supplementary Table 1***.

2.2. Methodologies for calculating water and carbon footprints of hydropower plants

To assess the hydropower *WF* & *CF* in China, all hydropower plants' *WF* and *CF* were calculated to ensure the accuracy of the results. In order to provide a complete picture of the WF and CF of hydropower in China, the missing data for Type II hydropower plants were estimated using Machine Learning and then the total hydropower production and the WF and CF and its intensity for both Type I and II plants were estimated at regional scales to provided the intensity for regional WF and CF assessment.

According to Wang et al [28], the whole life cycle water footprint (WF_{total}) of hydropower plants consists of evaporation (WF_e, greater than 99 % of WF_{total}), construction stage (WF_c), and operation stage (WF_o). In comparison, considering the evaporation water footprint alone, the water footprint in the operation stage only accounts for <0.1 % of the total water footprint [28], which can be ignored according to the life cycle assessment principle. Therefore, this study only considers the water footprints of evaporation and construction stage. The WF_e can be estimated according to meteorological data, and the formula is as follows:

$$WF_e = 10 \times E \times A \tag{1}$$

where, E is reservoir surface evaporation capacity, m^3; A is hydropower station's reservoir water surface area, hm^2. The E in formula (1) was calculated by using a reservoir surface evaporation optimization model. This model extends the Penman-Monteith (PAO) model equation into a multi-factor surface evaporation model that combines meteorological factors to estimate water surface evaporation. The calculation formula as follows:

$$\begin{gathered}
E = \Delta e \times f(\Delta T, r, W) \\
f(\Delta T, r, W) = g(\Delta T)\cdot\varphi(r)\cdot\varphi(W) \\
\varphi(W) = \begin{cases} 0.192 + 0.08W, & (W \leqslant 1.5\ \mathrm{m/s}) \\ 0.312 + 0.078(W - 1.5)^{1-0.098(W-1.5)^{0.5}}, & (W > 1.5\ \mathrm{m/s}) \end{cases} \\
\varphi(r) = 0.153 + 0.651(1 - r^2)^{1/2} \\
g(\Delta T) = 0.92 + 0.0363\Delta T^{1.08} \\
VPD = 0.611 \wedge \{(T_{a\times 17.27})/(T_{a+237.2}) \times (1 - r/100)\}
\end{gathered} \tag{2}$$

where, Δe is saturation vapor pressure differential; *$g(\Delta T)$* is function: change in water vapor temperature; *$\varphi(r)$* is function: relative humidity; *$\varphi(W)$* is function: wind speed; ΔT is the change in water temperature, ℃; *r* is relative humidity, %; W is wind speed, m/s; *VPD* is saturated vapor pressure, kPa; T_a is temperature, ℃.

To realize the quantitative assessment of WF_c and each stage of *CF* (also considering construction, operation stages) under the situation of data shortage, this paper uses machine learning (ML) methods to analyze the relevant factors and training models. First, we take Type I hydropower plants as samples to find the relationship between WF_i/CF_i (i means each stage, i = 1, 2, …) and hydropower plants parameters (dam height, storage, and installed capacity) using machine learning. In order to make the ML-model more accurate, we re-sampled 50 Type I hydropower plants, collected 564 typical hydropower stations widely distributed throughout China, in which the *WF/CF* of the hydropower plants are strictly one-to-one corresponded to the parameters of the hydropower plants, and constructed a basic database for training the machine learning model (the database was shown in Supplementary Information Table 2). Secondly, we simulate the WF_i/CF_i for each plant by the calculation model. And then, we combine the WF_i/CF_i and generated energy to calculate the hydropower WF_i/CF_i intensity at regional scales. The model constructing and calculating steps are shown in Fig. 2.

This research model is built using the Waikato Intelligent Analysis Environment (Weka, Waikato Environment for Knowledge Analysis), which is an open source machine learning and data mining software based on the JAVA environment [29]. Random forests (RF) model is an ensemble of many classifications or regression trees designed to produce accurate predictions, which do not over fit the data. It is a combination of tree predictors that depend on the values of random vectors sampled independently and with the same distribution for all trees in the forest [30]. This method has been widely used in ecology, environment, hydrology, and other fields [31,32]. In order to improve the samples distribution, the samples were resampled using bootstrapping method to establish a new data set. The Correlation-based Feature Subset Selection method [33] was used to combine the feature parameters that the Type I and Type II both has for WF/CF, the specific methods are in Supplementary Information.

2.3. WF & CF intensity and environmental pressure for hydropower at regional scale

To evaluate the regional total water footprint and carbon footprint of hydropower (at provincial scale), this paper introduces the intensity of water footprint and carbon footprint to distinguish the difference of efficiency of hydropower's environmental impacts among regions. The total water footprint and carbon footprint are calculated by the footprint intensity and hydropower generation. The formula of water footprint and carbon footprint intensity as followed:

$$WF_{int} = \alpha\hat{A}\cdot\frac{\sum_1^n WF}{\sum_1^n E} \tag{3}$$

$$CF_{int} = \alpha\hat{A}\cdot\frac{\sum_1^n CF}{\sum_1^n E} \tag{4}$$

where, α is the benefit apportionment coefficient for hydropower (see details in Supplementary Information); WF_{int} and CF_{int} are hydropower and water footprint and carbon footprint intensity ($m^3\ kWh^{-1}$, kg

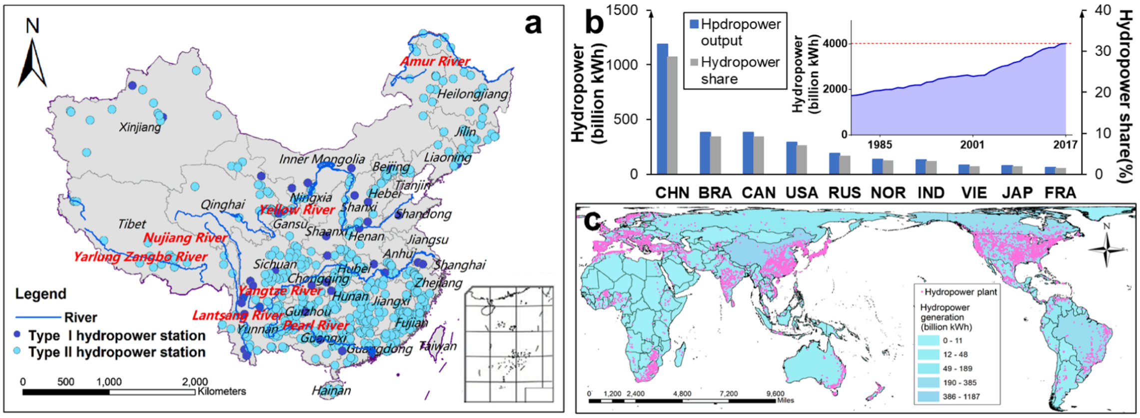

Fig. 1. Information about the research region: (a) Geographic distribution of hydropower plants and major rivers in China; (b) geographic distribution of hydropower plants at global scale; (c) global hydropower is developing rapidly and China has the highest share of hydropower generation in the world. (Note: The most large-scaled and medium-scaled hydropower plants in China are distributed in the south. They are not evenly distributed in space, which are closely related to the distribution of water resources. Global large and medium-sized hydropower plants are concentrated in Europe, East Asia, and North America.).

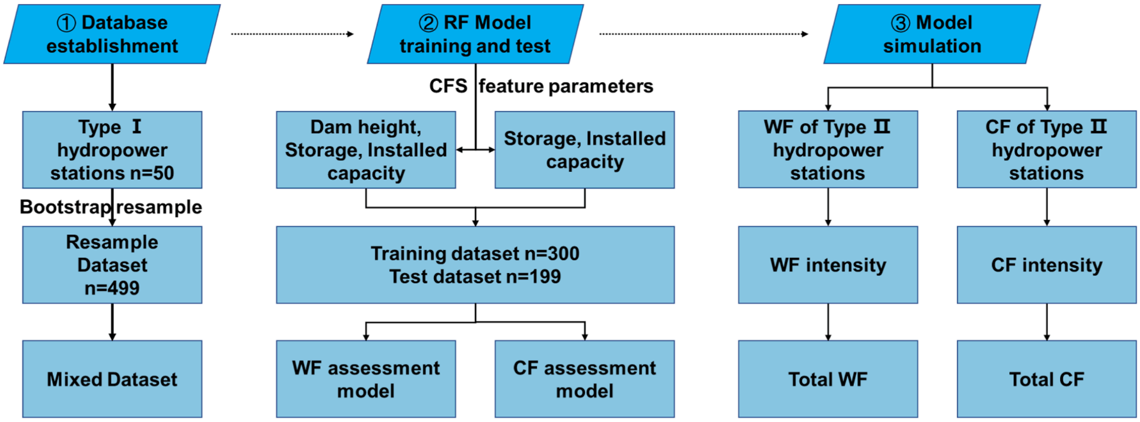

Fig. 2. Process of hydropower water and carbon footprint calculation.

eqCO_2 kWh^{-1}), E is hydropower generation (kWh) that calculated at inter-provincial scale, n is the number of hydropower plants.

$$WF_{total} = WF_{int} \times E_h \tag{5}$$

$$CF_{total} = CF_{int} \times E_h \tag{6}$$

where, E_h means actual hydropower generation volume of each province, the total WF and CF of hydropower generation in each province are WF_{total} and CF_{total}. The WF and CF of hydropower can quantitatively characterize the freshwater consumption and greenhouse gases emissions.

Combining the WF and CF with water resources and environmental indicators can comprehensively understand the impact of hydropower on resources and environment [34,35]. We use total regional available water resources and carbon emission to identify the water and carbon stress due to hydropower generation. The formula as follows:

$$WF_s = \frac{WF_{total}}{WR} \tag{7}$$

$$CF_s = \frac{CF_{total}}{CE} \tag{8}$$

where, WF_{total} and CF_{total} are the regional hydropower WF and CF (m^3, kg eqCO_2), WR is the total regional available water resources (m^3), and CE is the regional carbon emissions (kg eqCO_2). WF_s and CF_s are stress on regional water resources and carbon emission caused by hydropower development.

2.4. Impact factors of water and carbon footprint intensity

The WF_{int} and CF_{int} of hydropower are affected by natural and socioeconomic factors, including natural geographical features, climatic conditions, regional economic development level, and electricity consumption structure. This study selected 16 factors and did Pearson correlation analysis test with hydropower water and carbon footprint intensity. The significant test was analyzed under $\alpha = 0.05$ and 0.01 levels.

2.5. Sensitivity analysis and model verification

The improvement of the required accuracy of the estimation model puts forward higher requirements for the accuracy of the input data, and it is necessary to identify the influence of input data on output uncertainty. Sensitivity Analysis (SA) can understand the relative importance of each input data of the model. In the calculation process, the input parameters have certain uncertainties, so we assume that the error range of input parameters is between ± 10 %, re-input the model to calculate the new results, and calculate the reliability of the sensitivity analysis model. In this study, the sensitivity index [36] was used to quantify the impact of parameter fluctuations on the results:

$$Sx = \Delta Y / \Delta X \tag{9}$$

where, X is the reference value of the parameter, ΔY is the value fluctuation caused by the parameter change, and Sx is the sensitivity of the parameter. The baseline value of the parameters of the imported model is increased or decreased by 10 % (ΔX), and the water and carbon footprint of the hydropower plants is recalculated. Generally, if the $|Sx|$ is$<$0.2, the sensitivity analysis is verified.

2.6. Data sources and processing

The meteorological data in the study involved a total of 36 years of average temperature, relative humidity, average wind speed and other monthly meteorological data from 613 meteorological plants in 31 provinces from 1981 to 2017. All meteorological plants are China's reference surface meteorological observation plants. They are derived from the monthly data sets of China's surface meteorological data from the China Meteorological Data Network (https://data.cma.cn/). The data used in impact factor analysis comes from China Statistical Yearbook (1995–2017), China Electric Power Yearbook (1995–2017), etc.

The water and carbon footprint data of Type I hydropower plants are referred from Wang, Chen [28]. The statistical data of all hydropower plants involved in this study, including hydropower plant operation, construction, engineering construction time and other data are from "21st Century Hydropower Engineering", the compilation of Chinese Water Conservancy Yearbook (1981–2017), etc. The hydropower plants' geographical parameters are from "the China Construction Engineering Database-Water Conservancy and Hydropower Project" and extracted through the Global Dam Watch (https://globaldamwatch.org/) and Google earth. The hydropower generation data of China's provinces from 1995 to 2017 were sourced from China Energy Yearbook and China Statistical Yearbook. The carbon emissions data of each province were sourced from China Emission Accounts and Datasets (CEADs, Data Descriptor: https://www.ceads.net/). The Global hydropower and generation data from the GDW and U.S. Energy Information Administration (U.S. EIA, https://www.eia.gov). All data were subjected to analysis of correlation with SPSS. All result maps in this study were drawn by ArcGIS 10.1 (ESRI).

3. Results

3.1. WF & CF and spatial characters of hydropower plants in China

Fig. 3a shows the water footprints of hydropower plants in China are varying widely (5.7–86.8 billion m^3), their spatial distribution is relatively random and had no obvious clustering feature (Moran's I≈0).

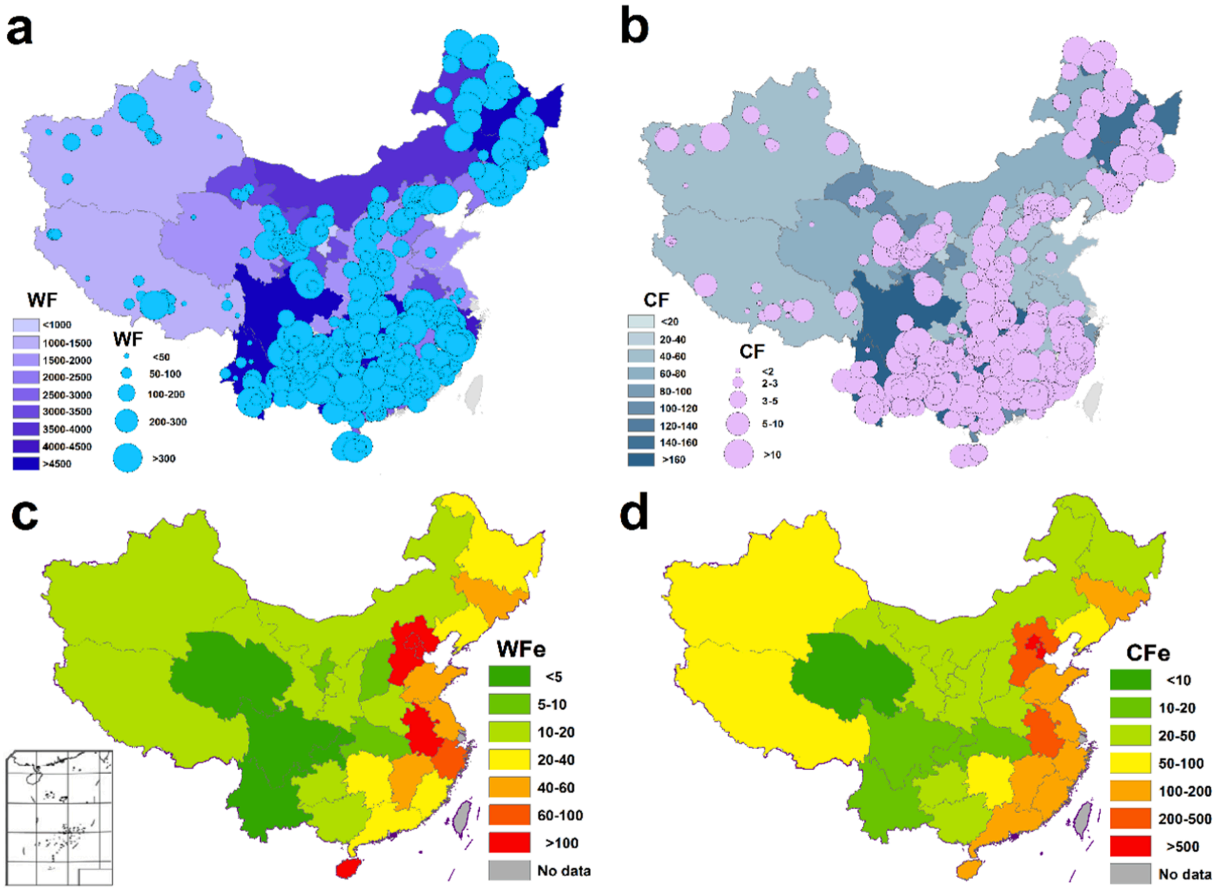

Fig. 3. Geographic distribution for Water and Carbon Footprints of hydropower plants and intensities: (a) water footprint (million m^3), (b) carbon footprint (million t CO_2); (c) water footprint intensity (m^3 per kWh), (d) carbon footprint intensity (kg CO_2 per kWh) (Note: The sizes of the circles represent the water and carbon footprint of each hydropower plants).

Affected by natural factors such as climate and terrain, the hydropower plants have significant differences in water footprints between provinces ($p < 0.05$, $t = 9.36$). Hydropower plants with larger water footprints are distributed in Guangxi, Yunnan, and Hubei provinces. The remaining are mostly distributed in the mid-west regions and inland provinces, there is no significant spatial auto-correlation feature. The carbon footprint values range for different hydropower plants are also large (0.4–23.5 million t $eqCO_2$), and the spatial distribution pattern is relatively consistent with the water footprint. Among them, the Hongjiadu Hydropower Plant (Guizhou Province, 27.04°N, 106.02°E) has the largest water footprint and the Xiangjia Dam Hydropower Plant (Yunnan Province, 28.46°N, 104.38°E) has the highest carbon footprint. The specific detailed results are summarized in ***Supplementary Table 1***.

Fig. 3c and Fig. 3d shows the water and carbon footprint intensity of hydropower plants are varying significantly. The hydropower water footprint intensity ranging from 1.1 to 301.0 m^3/MWh in each province, with an average value of 53.9 m^3/MWh. The water footprint intensity of eastern coast and North China are relatively high, particularly in Hebei, Beijing, and Anhui provinces. In contrary, the water footprint intensity in southwest, upper, and middle reaches of Yangtze River are showing the lowest, such as Qinghai, Sichuan, Yunnan, and Hubei provinces. Also, the hydropower carbon footprint intensity ranging from 4.1 to 860.7 kg $eqCO_2$/MWh, with an average value of 125.9 kg $eqCO_2$/MWh. The spatial distribution is relatively consistent with the water footprint. The eastern regions are significantly higher than the southwest regions. The largest provinces are also Hebei, Beijing, and Anhui. The provinces with smallest hydropower carbon footprint intensity are Qinghai, Yunnan, and Hubei.

In general, the total water and carbon footprint are shown in Fig. 3b, the provinces with the largest water footprint are Guangxi (856.8 billion m^3), Hubei (733.7 billion m^3), and Yunnan (722.0 billion m^3). They are spatially concentrated in the southwest and northeast regions, east China coastal areas (Fig. 3a). The carbon shows similar spatial distribution trend as water footprint. Where, the largest provinces are Guangxi (187.2 million t $eqCO_2$), Hunan (199.1 million t $eqCO_2$), and Yunnan (263.2 t $eqCO_2$). The hydropower water and carbon footprint at provincial level in China during 1995 to 2017 are detailed in ***Supplementary Table 3–4***.

3.2. Temporal variation of total WF and CF for hydropower plants in China

It can be seen from Fig. 4a that the rapid development of hydropower plants in China has increased the total WF and CF. The WF and CF during 1995 to 2017 have been increased by 9.8 billion m^3 to 29.5 billion kg $eqCO_2$, respectively. Based on the correlation between WF and CF with years, this paper divided research time scale into two different stages. Before 2000, there was no significant increasing trend ($p > 0.05$). The water and carbon footprint were increased slightly from 4.1 billion m^3 and 11.8 billion kg $eqCO_2$ to 5.1 billion m^3 and 13.1 billion kg $eqCO_2$ (the annual growth rate was 0.1 billion m^3 and 0.4 billion kg $eqCO_2$). While, during 2000 to 2017, the water and carbon footprint were increased to 13.9 billion m^3 and 41.3 billion kg $eqCO_2$ (with average annual growth of 0.5 billion m^3 and 1.8 billion kg $eqCO_2$). It is worth noting that from 2007 to 2012, China's total hydropower, WF & CF showed continuous and significant fluctuations, but did not affect the overall upward trend. The water and carbon footprint of the top 5 provinces with the largest hydropower generation over time is shown in

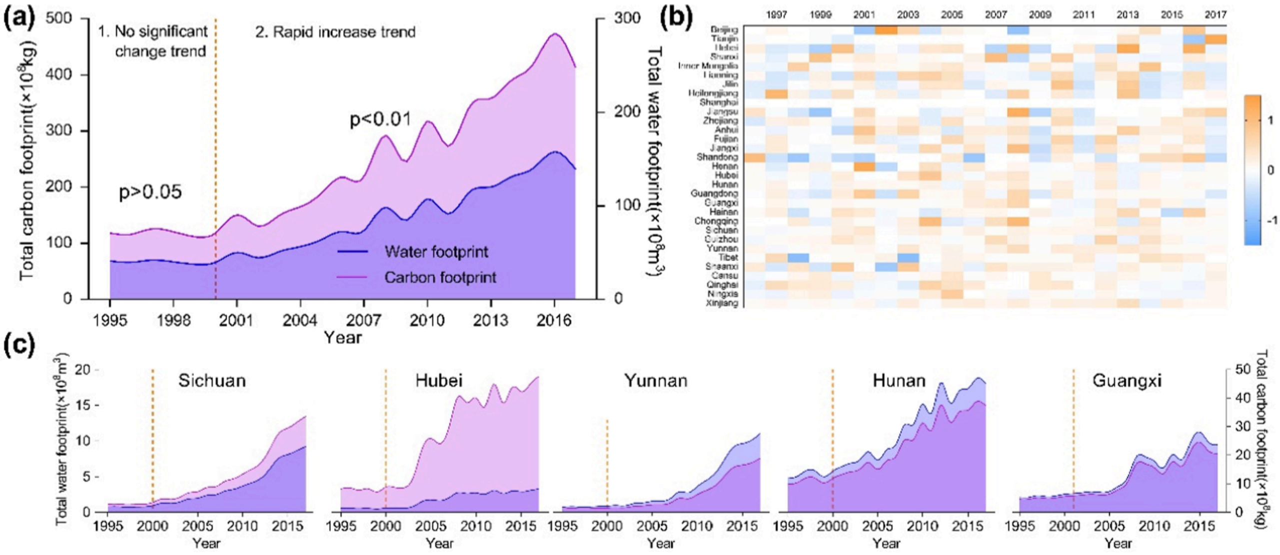

Fig. 4. Temporal variation WF & CF of hydropower in China. (Note: a. hydropower development in China was divided into two stages from 1995 to 2017, with the second stage showing a rapid increase. The p value in the figure means the significance between water or carbon footprint and years. p greater than 0.05, none significance; $p < 0.01$); b. Change rate of the hydropower water and carbon footprint of China's provinces over time; c. water and carbon footprints of the top 5 provinces with the largest hydropower generation.).

Fig. 4c. The characters of changes in different provinces is obviously different. Among them, Sichuan, Yunnan, and Hunan all show an upward trend year by year, but Hubei and Guangxi have seen obvious fluctuations, and even after 2008, they have been stable or even declining.

In general, WF & CF of most provinces in China shows the upward trend during study period, but few provinces and years shows the declined trend. According to the total water footprint data of each province from 1995 to 2017 (Fig. 4b), the three provinces with the largest increase in total water footprint are Hunan, Sichuan, and Fujian, increased by 10.9 (+278 %), 8.4 (+1070 %), and 7.9 (+193 %) billion m^3, while, only Tianjin, Liaoning, and Jilin have reduced their total water footprints by 0.03 (−67 %), 0.3 (−17 %), and 0.9 (−19 %) million m^3. The largest increase in the total carbon footprint of each province i.e., Fujian, Sichuan, and Yunnan, were increased by 33.4 (+193 %), 30.8 (+107 %) and 25.8 (+1439 %) billion kg eqCO_2 respectively. Similar with the water footprint, the total carbon footprints of Tianjin, Liaoning and Jilin have dropped by 0.1 (−67 %), 0.6 (−17 %) and 2.2 (−19 %) million kg eqCO_2 (*Supplementary Fig. 3*).

3.3. Analysis of impact factors of water and carbon footprint of hydropower

As shown in Table 1, the intensity of water carbon footprint is not significantly related to meteorological conditions such as geographic location, temperature, wind speed and radiation, but the intensity of water footprint is significantly related to atmospheric pressure and drought, but none of the above factors has a significant correlation with CF. The RDLS (Relief Degree of Land Surface) is related to the intensity of the water footprint, but not to the intensity of the carbon footprint. There is no significant correlation between the intensity of runoff and the WF_{int}/CF_{int}. Regarding economic and social factors, per capita GDP, urbanization rate, power load rate and water footprint intensity and carbon footprint intensity are all significantly related. However, there is no significant correlation between the average electricity price (that hydropower plants are sold to the National Electric Grid) and the electric

Table 1

Analysis of impact factors of water and carbon footprint intensity of hydropower.

Category	Impact Factor	Water footprint intensity		Carbon footprint intensity		N
		Pearson value	Significant	Pearson value	Significant	
Natural condition	Longitude (°)	0.345	0.062	0.274	0.143	30
	Latitude (°)	0.103	0.588	0.186	0.325	30
	Temperature (℃)	0.071	0.710	0.000	0.998	30
	Wind speed (m s^{-1})	−0.104	0.585	−0.138	0.466	30
	Atmospheric pressure (kPa)	0.403*	0.027	0.319	0.085	30
	Solar radiation (MJ m^{-2})	0.018	0.926	0.087	0.649	30
	Dry degree	0.590**	0.001	0.194	0.305	30
	Relief amplitude (RDLS)	−0.405*	0.027	−0.311	0.095	30
	Runoff intensity (m^3 km^{-1})	0.001	0.996	−0.100	0.600	30
Social background	GDP per capita (Yuan)	0.533**	0.002	0.680**	0.001	30
	Urbanization rate (%)	0.546**	0.002	0.651**	0.001	30
	Electricity price (Yuan kWh^{-1})	0.243	0.203	0.099	0.610	30
	Electric power load (%)	0.598**	0.001	0.686**	0.001	30
	Proportion of industrial electricity consumption (%)	−0.416*	0.022	−0.435*	0.016	30
	Proportion of household electricity consumption (%)	0.130	0.250	0.113	0.552	30
	Selling price of hydropower (Yuan kWh^{-1})	0.111	0.581	−0.025	0.902	30

Note:

[*] donates 5 % significant level (p value < 0.05).

[**] donates 1 % significant level (p value < 0.01).

retailed price. For the power consumption side, the share of industrial power consumption is significantly correlated with the intensity of WF and CF, but there is no significant correlation between residential power consumption.

3.4. Sensitivity analysis and uncertainty

The dam height, storage capacity, and installed capacity that have been selected in this study have significant impact on the results of water and carbon footprint calculated using the random forest method. The validation set model estimates that the relative average error is < 10 % and all passed the sensitivity test standard, the range of the results was within the acceptable range ($|Sx| < 0.15$), which proved that the model was relatively stable and reliable (see Fig. 5). The dam heights and installed capacity of hydropower projects are fixed and the data is reliable, which will not cause large measurement errors and increase the deviation of the calculation results. The storage capacity that has the greatest impact on the results, which is affected by hydrological and river conditions. At the same time, considering that some reservoirs have important storage and irrigation functions, the storage capacity will be more irregular. Moreover, the water surface area after impoundment is used to calculate evaporation, which will overestimate the water footprint. At the same time, we do fitting analysis for training set and simulating set with typical parameters. The results show that both water footprint and carbon footprint have consistent statistical characteristics with typical parameters (see details in Supplementary Fig. 6). Due to data limitations, there are few training set samples in northwest and northeast regions, which will also produce certain uncertainties for model training and results.

4. Discussion

4.1. Characters of water and carbon footprints for hydropower

Water crisis has become a global risk, affecting more than half of the world's population [37]. The comparison of hydropower water and carbon footprint intensity calculated in this study with the results of existing studies [24,27,34,38–40] are shown in Supplementary Fig. 2. hydropower water and carbon footprint intensity are significantly different between different countries. The huge differences in water footprint between different hydropower plants were caused by multiple factors such as climate, topography, and land type before flooding [41], however, the difference in evaporation, due to different climatic conditions is the most dominant factor. Bello et al [39] suggested that the WF of hydropower plants in topography complex regions is larger, these regions have abundant water resources, more rivers and larger water drop levels, which are suitable for the development of cascade hydropower plants. The eastern coastal areas are flat, with pumped storage power plants or hydropower plants with small heads, and low hydropower utilization efficiency [42].

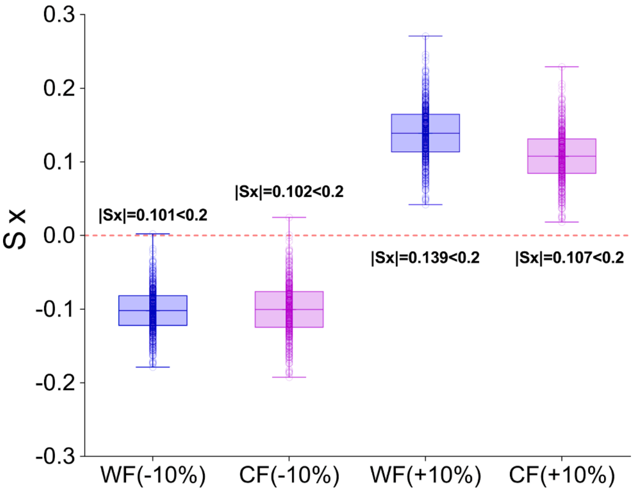

Fig. 5. Sensitivity analysis results of water and carbon footprint evaluation. (Note: The values in parentheses represent input parameter changes. The results showed that the model passes the sensitivity test, which proves that the simulation results are relatively stable under the premise of uncertainty in the parameters.).

Regarding the CF of hydropower, except for Romania, the CF of the United States and Brazil is smaller than China as estimated in this study. The CF of hydropower plants is also caused by various factors such as the input of construction materials and the type of submerged land. Since the impact of climate on the CF is not as strong as that of the WF, no significant impact has been found on it. However, it should be noted that the CF of hydropower in this study was estimated based on actual power generating unites. The power generation is much lower than the installed capacity, and the results are different from existing studies (estimated by installed capacity) [43]. The variation in runoff caused by climatic or hydrological situations, hydropower plants often fail to produce power generation according to the rated installed capacity [39,44]. It can also be found from Fig. 6 that the spatial distribution of the WF/CF per unit of economic benefit of power generation is also relatively heterogeneous, the east is significantly higher than that of central and western regions.

4.2. Water stress and carbon stress due to hydropower plants at multi-level scales

The construction and operation of hydropower plants have changed the original land water cycle process [45]. In order to maximize the benefits of hydropower, the peak flow power generation has been used to artificially change the river flow, and the original complementary relationship has been changed as well [46]. The coefficient of China's water stress due to hydropower is 0.26, which indicated that China's hydropower development alone accounted more than 1/4 of total available water resources (Fig. 7a). Comparing with the densely distributed hydropower plants in southwestern provinces such as Yunnan, Sichuan, and Guizhou, the pressure coefficients of water resources in Beijing and Jilin, located in the eastern plains found higher (Fig. 7a). Although the hydropower and WF of the southwestern provinces is large, the regional water resources endowment conditions are well, and the negative impact of water consumption in hydropower development is eliminated [47]. In contrast, in arid and semi-arid regions where water resources are scarce, and the hydropower development intensity is comparatively lower, but it has brought serious impact on the local water resources. It need to be more cautious for developing hydropower in such arid or mid-arid regions [48]. The hydropower development of WF will have dramatic impact on local water resources (watershed hydrologic cycle and climate change, etc.). From Fig. 7b, it is shown that the northern Europe and central Africa have higher water stress of hydropower electricity, the hydropower development has affected the water resources conditions and might cause risks of drought and climate changes. But from the perspective of the global hydrological cycle, the impact of hydropower water footprint on global hydrology and climate is minimal.

Due to the uneven level of economic development in different provinces, the CF_s distributed vary spatially, and generally show a trend of low in west and high in east. The 26 % provinces' CF_s is higher than 0.5, and the highest CF_s appeared in Yunnan Province (107 %). The hydropower CF largely increases the burden of emission reductions (see details in Supplementary Fig. 7). On one hand, provinces with sufficient hydropower resources, large-scale and densely-distributed hydropower plants such as Yunnan, have a large CF and improved the burden to emissions reduction. On the other hand, provinces with low economic development such as Tibet and Qinghai provinces, have low carbon emissions currently [49,50]. Their corresponding carbon reduction

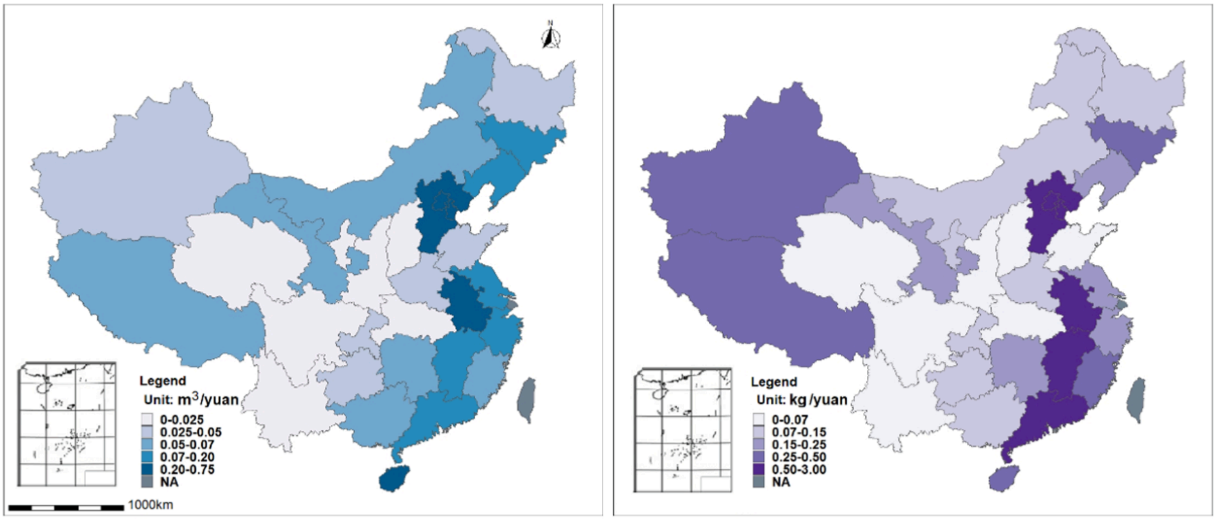

Fig. 6. Water and carbon footprint intensity of hydropower economic output at province level.

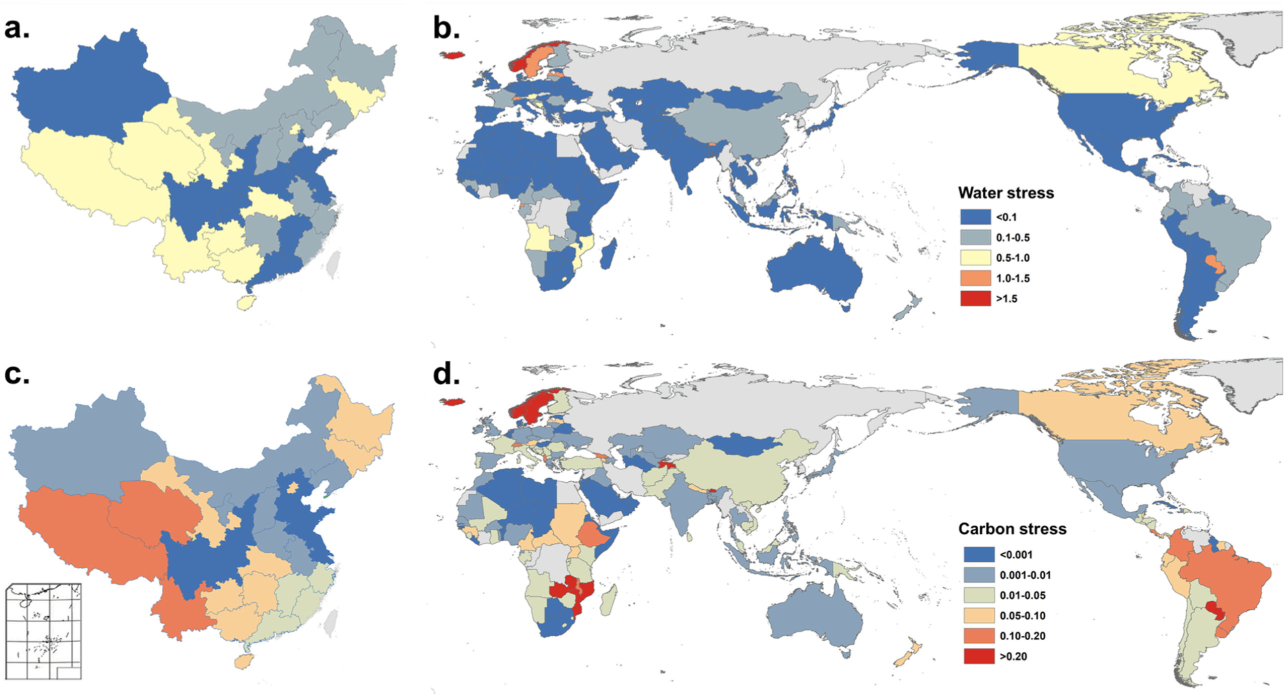

Fig. 7. Water stress and carbon stress due to hydropower electric at multi-level scales. (Note: a. Water stress in China, b. water stress at global scale; c. carbon stress in China, d. carbon stress at global scale).

targets are relatively small, and the hydropower CF has also significantly increased the local carbon reduction resistance. Hydropower is currently a relatively clean power generation method, which is of great significance for energy conservation and emission reduction [51,52]. The pressure coefficient of China's hydropower carbon emission reduction is 35 %, which showed that the "China's emission reduction plan-hydropower replaces thermal power" would generate a highly hidden carbon emissions indirectly increase the burden of emission reductions [53]. Different from WF, CF from hydropower development in each country will have an indelible impact on the global climate change. In 2017, more than 500 million tons of carbon was emitted from hydropower development in the world. Countries in South America, Africa and Europe have high carbon stress relatively, the Paraguay, Iceland and Bhutan all exceed more than 50 % particularly (Fig. 7d).

4.3. Suggestions for hydropower sustainable development

Although hydropower development consumes water, generates greenhouse gases and has a certain degree of impacts on environment, hydropower still has great advantages [26] at economic, technical, and environmental aspects [54]. In the future, it needs to be incorporated into planning and overall consideration of its environmental burden. The development of hydropower must be rationally planned in accordance with regional water resource, and strictly control the intensity of hydropower development to ensure the sustainability of water resources [55]. Considering the imbalance of regional water resources, it needs to consider the conditions of regional water resources, especially in arid or mid-arid regions worldwide. For example, the Three Gorges has flooded a total area of 79,000 km^2 and 19,400 hm^2 of arable land, involving 1.17 million migrants [56,57]. If it not properly dealt, the construction of hydropower plants may lead to new risks of soil erosion and environmental pollution, which will increase the possibility of geological disasters such as landslides [58]. It will also have a certain impact on the living environment of aquatic organisms and rare species [59,60].

Although the International Hydropower Association proposed to accelerate the hydropower carbon footprint reporting mechanism to promote the achievement of carbon reduction targets, the current carbon footprint assessment standards and systems are still being constructed [61]. Previous assessments did not consider the carbon footprint of hydropower itself, and the actual CO_2 emission reduction is 134 million t $eqCO_2$ (-16.58 %), and the emission reduction effect is overestimated by 11.72 %, which is far less than the estimated carbon emission reduction target [62], and cannot fulfill regional emission reduction commitments in 2020 (reduce 40–45 % compared to 2005 emission standard). It still needs to increase the development of hydropower [63] or other clean energy sources such as solar, biomass and wind power energy, etc. to replace at least 220 million kWh of thermal power in order to meet the greenhouse gas reduction commitment. Also, in the western development strategy, the transformation of thermal power and the reduction of the intensity of thermal power development in the eastern region are proposed, and the potential water footprint and carbon footprint should also be considered. According to EIA, global hydropower installed capacity will reach 1750 GW in 2035 (the rate of exploitation will reach to 38.6 %), including Africa, South Asia and other regions have great potential for hydropower development. It suggested that the environmental impact should be consider in regional hydropower development program, otherwise while meet the demand of energy, but still will produce a great environmental negative effect.

Future research can optimize and improve the hydropower plants construction and operation stages to reduce the hydropower water and carbon footprint [64]. For example, it is recommended to adopt low-carbon materials or technologies during the construction phase of the projects. This study can provide deep insights decision support for energy production, power development planning and policy formulation. It is recommended that the water and carbon footprint should be included in the environmental assessment of hydropower project construction. At the same time, it should be combined with regional water resources, economic cost, and safety assessment to provide cleaner hydropower [7,65]. Due to the limited data and the hydropower plant information management system to be improved, this study only considered large and medium-sized hydropower plants, and did not involve small hydropower projects (SHP). It can be found that the smaller the scale of hydropower plant, the higher intensity of its WF/CF existed (see details in ***Supplementary Fig. 6***). Therefore, compared to large and medium-sized hydropower plants, SHP have a greater impact on local water consumption and carbon emissions. But with the marketization of hydropower development, small hydropower has been rapidly promoted [66] with serious environmental impacts occurred meanwhile [67]. Small-scale hydropower projects have large proportion of irrigation, water saving and storage functions. The energy efficiency was low and the CF may be larger than large or medium-sized hydropower plants. Ignoring the CF of the SHP may result in underestimating the impact of hydropower development on environment furtherly. In future, it is necessary to carry out watershed coordination planning for SHP [68], include statistical work and assess the impact of SHP on environment.

5. Conclusion

In this paper, it is found that the water footprint and carbon footprint generated by hydropower cannot be ignored while hydropower ensuring human life and promoting economic development, it is not the real zero-emission clean energy. The water and carbon footprints of China's hydropower has been increased largely during 1995–2017, particularly after 2001. As for 2017, these values reached to 13.90 billion m^3 and 413.40 billion kg $eqCO_2$. The hydropower water and carbon footprints intensity in China were 53.95 m^3/MWh and 125.89 kg $eqCO_2$/MWh, which are at a highest level around the globe. The spatial distribution of environmental burden contrasts with the benefits of hydropower resources, showed low in the west and high in the east regions. Hydropower poses big burden on regional water resources and carbon emissions. China's hydropower water footprint accounted for 26 % of total available water resources, and carbon footprint of the hydropower is up to 35 % of the regional total carbon emission reduction target. Reconsidering the China's emissions reduction plan, one of the essential methods that using hydropower instead of thermal power, which effect is overestimated by 11.72 %. The research on hydropower water and carbon footprint has improved the gap of hydropower environmental impact assessment, future research might focus on comprehensive risks of hydropower development and its impact on regional water-energy-environment nexus, thus promoting the realization of sustainable development Goal.

Data and materials availability.

All data and codes are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Xiuzhi Chen: Conceptualization, Methodology, Software, Data curation, Writing – original draft, Writing – review & editing. **Chang Liu:** Methodology, Software, Data curation, Writing – original draft. **Pieter van Oel:** Methodology, Writing – review & editing. **Mesfin Mergia Mekonnen:** Methodology, Writing – review & editing. **Kelly R. Thorp:** Writing – review & editing. **Tuo Yin:** Writing – original draft, Writing – review & editing. **Jinyan Wang:** Data curation. **Tahir Muhammad:** Writing – review & editing. **Yunkai Li:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision.

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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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2022.119872.

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