

Article

Hydropower Generation Vulnerability in the Yangtze River in China under Climate Change Scenarios: Analysis Based on the WEAP Model

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Received: 29 September 2017; Accepted: 6 November 2017; Published: 13 November 2017

Abstract: Global warming caused by human activities exacerbates the water cycle, changes precipitation features, such as precipitation amount, intensity and time, and raises uncertainties in water resources. This work uses run-off data obtained using climate change models under representative concentration pathways (RCPs) and selects the Yangtze River Basin as the research boundary to evaluate and analyse the vulnerability of hydropower generation in 2016–2050 on the basis of the water evaluation and planning model. Results show that the amount of rainfall during 2016–2050 in the Yangtze River Basin is estimated to increase with fluctuations in RCP4.5 and RCP8.5 scenarios. In the RCP4.5 scenario, hydropower stations exhibit large fluctuations in generating capacity, which present the trend of an increase after a decrease; in the RCP8.5 scenario, the generating capacity of hydropower stations in the Yangtze River Basin presents a steady increase. Over 50% of the generating capacity in the Yangtze River Basin is produced from the Three Gorges Dam and 10 other hydropower stations. Over 90% is generated in eight river basins, including the Jinsha, Ya-lung and Min Rivers. Therefore, climate change may accelerate changes in the Yangtze River Basin and further lead to vulnerability of hydropower generation.

Keywords: climate changes; hydropower generation; vulnerability; the Yangtze River; China

1. Introduction

Hydropower has been an important part of clean energy supply in China. Statistics from the China Electricity Council indicated that the installed capacity of hydropower increased from 110 GW to 330 tGW from 2004 to 2016. The proportion of national total installed capacity varied from 24.5% to 20.0%. The electricity generation of hydropower increased from 3.535 trillion kWh to 1.1807 trillion kWh, and the proportion relative to the national total generating capacity increased from 16.0% to 19.7% [1]. The installed capacity of hydropower should reach 400 GW in 2030 to achieve the target of CO₂ intensity of GDP for China in 2030 [2].

In 2014, the United States and China created the US–China Joint Announcement on Climate Change, in which the Chinese government aims to achieve peak CO₂ emissions in 2030 and to exert best efforts to peak early, intending to increase the sharing of non-fossil fuels in primary energy consumption to approximately 20% by 2030 [3]. In 2015, the State Council released the Enhanced Actions on Climate Change: China’s Intended Nationally Determined Contribution (INDC), which further defines the measures and actions on climate change and propose high requirements for renewable energy development [4].

The latest INDC policy scenario created by the International Energy Agency forecasts that the electricity demand in China will increase by 75%, nearly twice the electricity demand in the United States, indicating the second largest electricity consumer in the world [5]. The generating capacity of renewable energy will comprise approximately 38% of the total generating capacity by 2030 to meet the increasing demand for electricity; the generating capacity of hydropower will constitute approximately 15% of the total generating capacity. Thus, hydropower generation will continue to play an important role in the next period. A water resource survey data in 2001 [6] showed that 5748 technically exploitable hydropower stations are in the Yangtze River Basin, with a total annual generating capacity of 1.19 trillion kWh and a total installed capacity of 256 million kW. The Yangtze River Basin has the greatest amount of technically exploitable hydropower resources nationwide, representing 47% of the nationwide total. In the national hydropower generation system, the Yangtze River flows through 11 provinces, cities and autonomous regions, including Yunnan, Sichuan, Hunan and Hubei; therefore, the hydropower generation system of the Yangtze River Basin occupies an important position in the national renewable energy supply network.

Global climate change will exert certain impacts on global precipitation and water resources. The fifth Intergovernmental Panel on Climate Change (IPCC) assessment report showed that the global average land and ocean surface temperatures increased by approximately 0.85 °C from 1880–2012. In this period, the global average surface temperature increased by 0.5 °C to 1.3 °C because of the adverse effects of greenhouse gases in 1950–2010, and precipitation in different regions of the world presented various trends [7]. Shi Peijun et al. [8] conducted studies on the features of precipitation changes. They divided China into two warm–dry trend zones, i.e., North China–North China and Southwest China–South China, and three warm–wet trend zones, i.e., Southeast Tibet–Southwest China, North China–North China and Northwest China–Qinghai–Tibet Plateau, based on the precipitation and temperature conditions in different regions in China in 1961–2010. They found that precipitation varied with different regions. Global climate change will lead to climate warming, increased evaporation, changes in precipitation and snowfall and high flood intensity and frequency. Global climate change will also cause changes in and affect the potential installed capacity of hydropower stations in operation and increase the risks of physical damages to hydropower stations in operation. This phenomenon highlights the vulnerability of hydropower generation systems to global climate change [9]. The concept of vulnerability was first proposed by Timmerman, and this concept is applied to social economic research [10] to explore the effects of climate change, especially on extreme natural disasters in the society. Subsequently, vulnerability is applied to biology, climate change, sustainability science, land use change and other fields [11].

2. Literature Review

Article 8 of the Paris Agreement describes that ‘Parties recognise the importance of averting, minimising and addressing loss and damage with the adverse effects of climate change and should enhance understanding, action and support on a cooperative and facilitative basis, including comprehensive risk assessment and management’ [12]. Hence, one main target for tackling climate change is to control the worst ending under accepted situations. Further research is required to understand the sustainable development of energy systems. Risk management and control have recently become increasingly popular perspectives amongst climate change fields. The concept of vulnerability was introduced to demonstrate the sensitivity of energy systems to climate change and has been applied to sustainable development of hydropower generation since 2000. Harrison et al. [13] studied the sensitivity of hydropower generation at the Batoka Gorge in Louisiana, USA, to climate change and analysed changes in hydropower under different climate scenarios, in which the notion of climate change vulnerability was introduced to describe climate as an external disturbance factor. Lucena et al. [14] studied the vulnerability of renewable energy power generation in Brazil, which was measured by the percentage of deviation in estimated electricity output from the baseline scenario, under the IPCC climate change scenarios. Ospina Norena et al. [15] analysed the vulnerability of

hydropower generation, which was measured by the annual average rate of changes in hydropower, at the Sinu-Caribbean Basin in Columbia under the IPCC model scenarios. Van Vliet et al. [9] studied the vulnerability of electric power systems in the context of global climate change by taking the percentage of annual average change in available installed capacity as the vulnerability index; they probed the vulnerability of future thermal power and hydropower generation under scenarios representative concentration pathway RCP2.6 and RCP8.5 for five general circulation models (GCMs). Ospina Norena et al. [15] investigated the vulnerability of hydropower generation at the Sinu-Caribbean Basin in Columbia under the IPCC greenhouse gas emission scenario and forecasted the change in hydropower under climate change in the area in 2010–2039 through the water evaluation and planning (WEAP) model, which indicated that the change ranged from 0.6% to 35.2%. Beyene et al. [16] simulated the changes in water resources in the Nile Valley until 2099 under the GCMs and A2 and B1 emission models provided in the fourth assessment report of the IPCC; they estimated the possible effects on hydropower generation. Almost all studies have selected changes in installed capacity or electricity generation of hydropower to demonstrate the impacts of water resources under climate change scenarios.

Several studies have analysed the changing mode of hydropower generation in an area with detailed time variables, e.g., month, and focused on the effects of changes in precipitation models on run-off to obtain additional specific hydropower variations to guide future operations of power stations. Vicuna et al. [17] used 11 power plants in Sierra Nevada, California, USA, as an example, and studied changes in hydropower under climate change, especially changes in hydropower in different months in the case of varying precipitation models, and introduced energy price and other economic factors to discuss the necessity of energy storage. Weingartner et al. [18] expressed that run-off had no significant change during summers but presented a notable increase during winters in the Alps; this result suggested the extent of the effects of climate change on hydropower systems by 2050 in Switzerland, especially the Alpine area. Renöfält et al. [19] selected Sweden for a case study on the effects of climate change on hydropower generation in different seasons and the corresponding ecological consequences of any change in power generation factors. Anugrah et al. [20] surveyed, simulated and forecasted the effects on hydrological models and hydropower generation in the Bayang Catchment and two other areas in Indonesia under different greenhouse gas emission scenarios presented in an IPCC report for 2013–2025. Mehta et al. [21] simulated the effects on hydropower generation in four river basins in Sierra Nevada, California, under different climate change scenarios (2, 4, 6 °C) for 1981–2000. Such studies have provided much seasonal information for hydropower changes and can offer support for detailed policy design.

Numerous researchers have expanded their study regions. Hamududu Byman et al. [22] indicated that climate change would not exert significant global impacts on hydropower generation until 2050, but the difference amongst regions was significant, e.g., hydropower supply might increase in Canada and Northern European countries but might sharply decline in Australia and other countries. Van Vliet et al. [9] arrived at a different conclusion; they simulated the effects of different RCP emission concentrations on the effective installed capacity of global hydropower and thermal power projects under the GCM and stated that the global effective installed hydropower capacity will decrease by 1.2% to 3.6% by 2050 and 0.4% to 6.1% by 2080. Such study results significantly varied by region, thereby showing regional differences in water resource availability and hydropower supply vulnerability.

Vulnerability research has become an important criterion that measures the effects of climate change on hydropower systems in the field of hydropower generation. Two indexes, namely, relative changes in electricity output and in available installed capacity, exist, although research indexes vary with methods. The influential mechanism of climate change on energy systems is complex and sensitive, and changes under the influence of climate change will vary greatly from area to area in China. Therefore, the vulnerability of hydropower systems in the Yangtze River Basin to global climate change scenarios was evaluated in this study. RCPs were selected as climate change scenarios, and data on run-off changes in the basin were obtained through climate change and concentration models.

Hydropower vulnerability in the basin during 2016–2050 was simulated using the WEAP model. This study also compared different scenarios and provided insights into uncertainties in future hydropower development under scenarios.

3. Modelling Tools and Methods

The WEAP model [23] is an integrated planning tool for water resources that can solve water resource protection, hydropower generation, reservoir operation, groundwater and surface water simulation and vulnerability evaluation. This study analyses the vulnerability of hydropower stations within the Yangtze River Basin and its tributaries for various global climate change scenarios from 2016–2050 based on the WEAP model and with the Yangtze River Basin in China as the research boundary and object and 2015 as the base year. The main technical routes of this work include boundary setting, benchmark setting, key hypotheses, scenario building, simulated calculation and evaluation.

(1) Boundary setting: This work involves the entire Yangtze River Basin (including its tributaries) which covers the stem stream, 17 primary tributaries, namely, Jinsha, Jialing, Ya-lung, Minjiang, Tuojiang, Qingyijiang, Wanhe, Wujiang, Yuanjiang, Ba, Han, Qingjiang, Xiangjiang, Zishui, Ganjiang, Xiu and Yulin Rivers, and over 50 corresponding secondary tributaries located mainly in 10 provincial administrative regions, i.e., Yunnan, Sichuan, Anhui, Gansu, Guizhou, Hubei, Hunan, Jiangxi, Shaanxi and Chongqing. This work forecasts the condition of hydropower generation from 2016–2050 with 2015 as the base year and year as the time step. Rivers and tributaries are expressed as lines and connections in terms of system architecture, and power stations are expressed as nodes.

(2) Benchmark setting: This route aims to obtain data on the name, geographic position, dam height and river basin of each power station within the Yangtze River Basin and data on installed capacity, overall generating efficiency and run-off in various areas from 2015. Data are input into the WEAP model. Verification and calibration are conducted on the basis of parameters in 2015 to determine the proportion of hydraulic head at a power station in the base year in dam height by multiplying overall efficiency to ensure accuracy of scenario evaluation.

(3) Key hypotheses: Two hypothetical scenarios in the WEAP model, namely, RCP4.5 and RCP8.5, and input run-off values of different power stations under corresponding RCP scenarios from 2016–2050 are established.

(4) Simulated calculation and evaluation: This route is conducted to calculate the energy output of each power station for two RCP scenarios from 2016–2050, summarise the variation trend of the electricity outputs of hydropower stations in different provincial administrative regions within the Yangtze River Basin and along primary tributaries and compare the vulnerability of hydropower generation within the Yangtze River Basin in different scenarios.

The WEAP model aims to incorporate these various values into an entire system. This model is an integrated approach to evaluating water and hydropower systems and their policy implications. As a dataset, this model also provides a system for maintaining water supply and use information.

4. Data Collection and Processing

4.1. Determination of the Boundary of the Yangtze River Basin

The Yangtze River Basin plays a significant role in hydropower generation systems in China through the concentrated hydropower resources of this river basin. The Yangtze River, the third largest river in the world and the largest one in China, covers a basin area of 1.80 million km², comprising 19% of the national territorial area of China. The nearly 6300-km-long river runs through 11 provincial administrative regions, i.e., Yunnan, Sichuan, Anhui, Gansu, Guizhou, Hubei, Hunan, Jiangxi, Shaanxi, Chongqing and Shanghai. The 2001 China Hydropower Resources Census indicated that the Yangtze River Basin accommodates 5748 technically exploitable hydropower stations, with an annual potential electricity output reaching 1.19 trillion kWh and a potential installed capacity reaching 256 million kW, and ranks the first in terms of technically exploitable hydropower resources which constitute 47% of the

total nationwide. The exploitable installed capacity of the Yarlung Zangbo River Basin is 68 million kW that represents 13% of the total, whereas that of the Yellow River Basin is 37 million kW that represents 7% of the total. Figure 1 illustrates the technically exploitable hydropower resources in different river basins. The Yangtze River Basin has 107 large hydropower stations with an installed capacity of 300 MW and above, with a total of 190,000 MW and generating electricity of 0.86 trillion kWh. The Yangtze River Basin has more than 50 hydropower stations with 1000 MW capacity and three stations with 10,000 MW capacity. This work focuses on the vulnerability of hydropower generation within the Yangtze River Basin to ensure data representation.

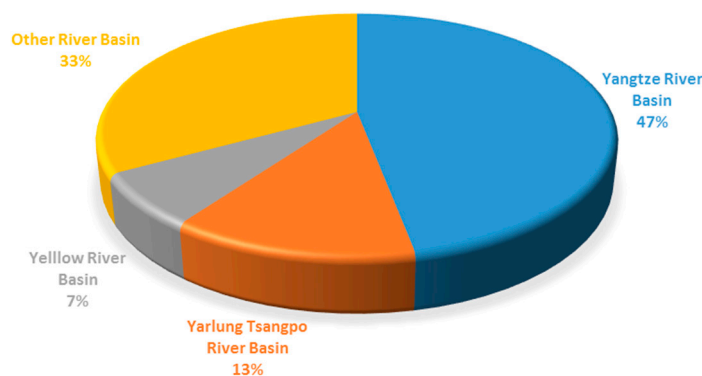


Figure 1. Proportions of technically exploitable hydropower resources in different river basins in China (2001 China Hydropower Resources Census).

4.2. Data Sources

The WEAP model has several data requirements, including the hydraulic head at a power station, generating efficiency and effective run-off through turbines, combined with the requirement for corresponding descriptions of power stations and rivers for electricity output estimation. The hydrological data in this work include the name, geographic position, dam height, installed capacity, base year, electricity output, overall generating efficiency and basin of each power station within the Yangtze River Basin. The data on the name and dam height of each covered power station come from the Large Dam Safety Supervision Centre (LDSSC), National Energy Administration [24], those on installed capacity and base year electricity output are from the Statistics of Electric Power Industry (SEPI) [25], and those on geographic position and basin are collected by Google search [26]. Run-off data are mainly obtained through the Coupled Model Intercomparison Project (CMIP5) under different RCP scenarios, which come from relevant studies on climate change research modes by the Centre for Earth System Science (CESS), Tsinghua University.

4.3. Data Matching

This work obtains data on 265 hydropower stations within the Yangtze River Basin, including 235 stations with data on annual electricity output in 2015 and 259 stations with matched longitudes and latitudes. Two hundred twenty-eight matched hydropower stations are screened out, including four stations with a capacity of 10,000 MW and above, 26 hydropower stations with 1000 MW to 10,000 MW capacity, 104 stations with 100 MW to 1000 MW capacity and 94 stations with 100 MW capacity. Statistics shows that the total installed capacity of all matched hydropower stations in this work reaches 157 million kW, which covers 49% of the nationwide total. The annual electricity output in 2015 was 0.60 trillion kWh, which covered 53% of the nationwide total. This work shows a high degree of data matching, and the coverage data can reflect the hydropower generation within the Yangtze River Basin and significantly represent changes in hydropower generation systems in China.

These power stations are encoded in the form of 'alphabet + alphabet + numeric' because of numerous covered power stations and corresponding river basins and cities. The first alphabet

represents a provincial administrative region; the second alphabet represents the stem stream of the Yangtze River or a primary tributary; the two-digit numeric value represents the number of the power station in the provincial administration and river basin (see Appendix A for detailed power station codes). Appendix B describes rivers and hydropower stations, particularly the aforementioned power stations, within the Yangtze River Basin on the basis of the WEAP model.

4.4. Data Calibration

The electricity output of a hydropower station is calculated by

$$GJ_{hydro} = Q \cdot H \cdot \eta \cdot \rho \cdot g \cdot t \quad (1)$$

where Q represents the effective run-off through turbines at the power station, m^3/s ; H is the hydraulic head, m ; η is the overall efficiency of the power station, which is affected by operating rate and generating efficiency of the power station; ρ is the water density, kg/m^3 ; g is the acceleration of gravity which is $9.806 m/s^2$; t is the annual time; and GJ_{hydro} is the annual electricity output, GJ .

The generating efficiency and hydraulic head of a power station are unavailable because of data limitation; thus, calibrating the base year is required to obtain the product of the proportion of hydraulic head at a power station in the base year to dam height and overall efficiency. The names and dam heights of the covered power stations sourced from LDSSC and the installed capacities and base year electricity outputs sourced from SEPI are first matched. The product of the proportion of hydraulic head at a power station in its dam height and overall efficiency are then estimated on the basis of the base year energy output. Uncertainty exists because run-off data are obtained at a resolution rate of $0.5^\circ \times 0.5^\circ$, which indicates a wide range covered by 111 and 85 km on latitude and longitude, respectively. Thus, this work explores the average run-off on the LDSSC and other websites with respect to a hydropower station with calibrated parameters greater than 1. The nearest run-off value to the average value from the run-off values surrounding the grid point of the calibrated run-off of the hydropower station in the scenario and at the time point is considered.

4.5. Run-Off Data Coupling

In this work, run-off data coupling is based on community land model (CLM) outputs from a CLM for scale-adaptive river transport (MOSART) coupling by CESS. The CLM is derived from the research by Dai et al. in 2013 and is a typical third-generation land surface model which considers carbon cycle function and describes land–air physical, chemical, biological and hydrological processes in a detailed manner; thus, CLM is easily coupled with large-scale climate and atmospheric models [27]; MOSART, which is a scheme of confluence for coupling to CLM, is obtained from the research by Li et al. in 2013 [28]. Climate data are obtained from the mean result of the evaluation of 36 global climate models conducted by the National Centre for Atmospheric Research [29].

In the scenario design, this work applies RCP scenarios to CMIP5 for simulating new climate models [30]. The proposition of the IPCC RCP scenarios allows simulating emission scenarios with a climate model [31]. Table 1 describes RCP scenarios. In this work, scenarios RCP4.5 and RCP8.5 are selected for a comparative study.

Table 1. Description of different climate change scenarios.

Scenario	Pathway Form	Radiation Intensity	Concentration Eq.
RCP2.6	Rise and fall	Peak at approximately $3 \text{ W} \cdot \text{m}^{-2}$ by 2100 and begin to fall	Reach approximately 490 CO ₂ -eq by 2100
RCP4.5	Achieve stability and maintain below the target	Keep stable at approximately $4.5 \text{ W} \cdot \text{m}^{-2}$ after 2100	Keep stable at approximately 650 CO ₂ -eq after 2100
RCP6.0	Achieve stability and maintain below the target	Keep stable at approximately $6.0 \text{ W} \cdot \text{m}^{-2}$ after 2100	Keep stable at approximately 850 CO ₂ -eq after 2100
RCP8.5	Constantly rise	Rise to more than $8.5 \text{ W} \cdot \text{m}^{-2}$ in 2100	Rise to more than 1370 CO ₂ -eq in 2100

This work covers the Yangtze River Basin at a precision of $0.5^\circ \times 0.5^\circ$ since 2015, with the simulation targeting 2016–2080.

5. Simulation Results

5.1. Run-Off Simulation

China water resources were unevenly distributed in 2015. The run-off of Heilongjiang, Yellow, Yangtze, Pearl, Lancang and Nujiang River systems is high, can reach at least 2000 m³/s, and reaches 100 m³/s to 2000 m³/s in other river basins in China. The river distribution in China renders high run-off in Southwest and South China but low run-off in Inner Mongolia, Qinghai and Xinjiang, which is typically below 30 m³/s.

The changes in run-off in 2030 and 2050 over that in 2015 for two global climate change scenarios, i.e., RCP4.5 and RCP8.5, show that the speed and trend of changes in run-off greatly vary from each region worldwide in the RCP4.5 climate change scenario. From 2030, extreme weather may occur worldwide, with the run-off in many regions possibly increasing by more than 100% or decreasing by more than 60%. This phenomenon is also true in China, where run-off will increase in most areas and significantly increase or decrease in certain areas. Overall, the run-off in several or most areas within the Yangtze River Basin will rise sharply in the future (Figure 2). Under the RCP4.5 scenario, the run-off of the Yangtze River Basin, Yellow River Basin and Haihe River Basin in 2030 will increase by more than 100% relative to that in 2015, whereas that of other basins will decrease. In 2050, the run-off of the western part of the Yangtze River Basin will still increase by 100% relative to that in 2015, whereas the run-off in some areas in South China will decrease. Under the RCP8.5 scenario, the probability of extreme weather is high, and the run-off in most areas of China will increase. The run-off within the Yangtze River Basin will rise by more than 100% in 2050 relative to that in 2015.

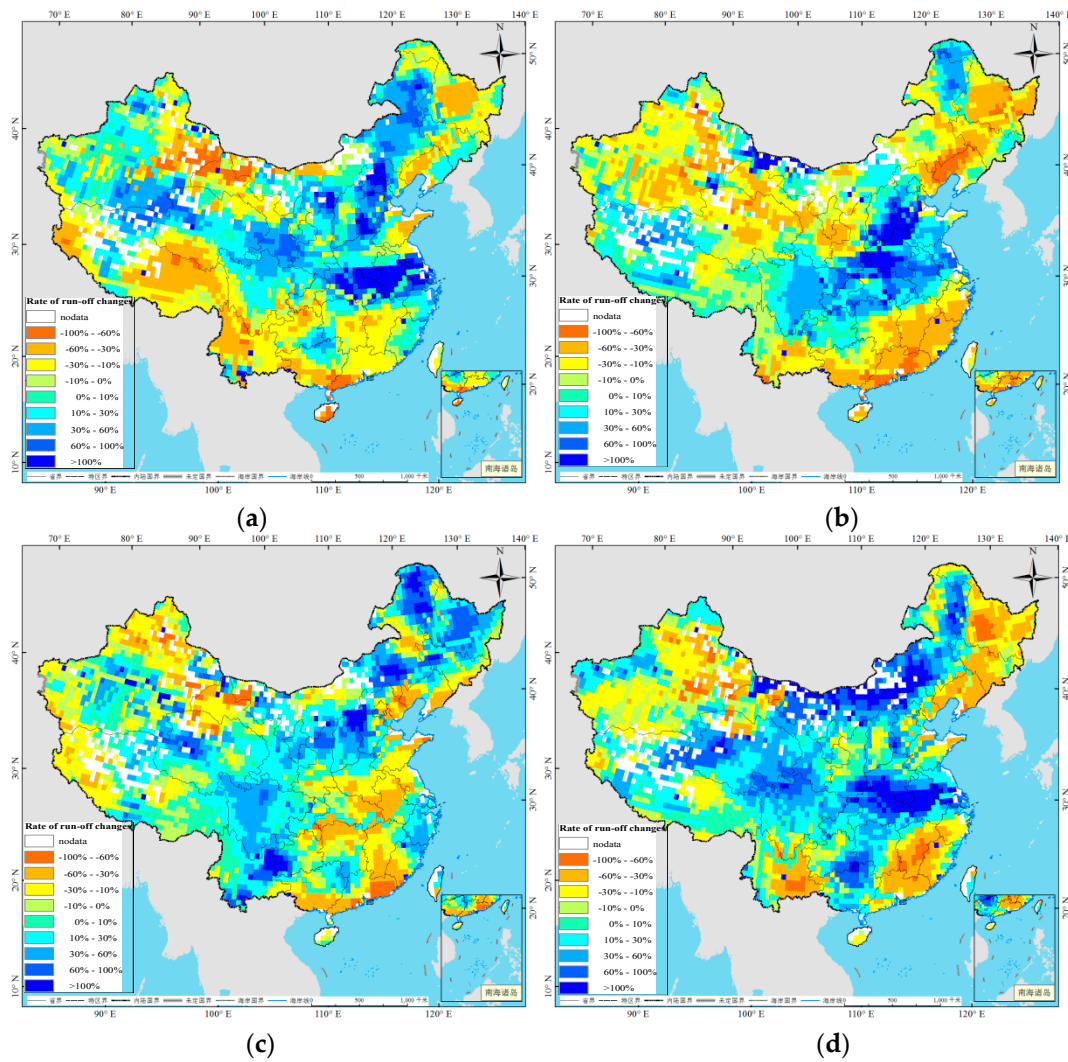


Figure 2. Rate of run-off changes in China (%). (a) Rate of changes in 2030 relative to that in 2015 (RCP4.5); (b) Rate of changes in 2030 relative to that in 2015 (RCP8.5); (c) Rate of changes in 2050 relative to that in 2015 (RCP4.5); (d) Rate of changes in 2050 relative to that in 2015 (RCP8.5).

5.2. Simulated Results of Hydropower Generation

The WEAP model simulation indicates that the electricity output of the covered hydropower stations within the Yangtze River Basin steadily rises in the RCP4.5 scenario, as illustrated in Figure 3. The estimated electricity output will be 531,219 million kWh in 2030, decreasing by 11.12% compared with the 597,707 million kWh in 2015. The electricity output in 2050 is estimated to be 771,753 million kWh, increasing by 29.12% over 2015.

Under the RCP8.5 scenario, the electricity output of the covered hydropower stations within the Yangtze River Basin in 2015 was 597,707 million kWh. The output is estimated to be 653,615 million kWh in 2030, which indicates a 9.35% increase over 2015 and to be 625,410 million kWh in 2050, which presents a 4.63% increase over 2015 (Figure 4).

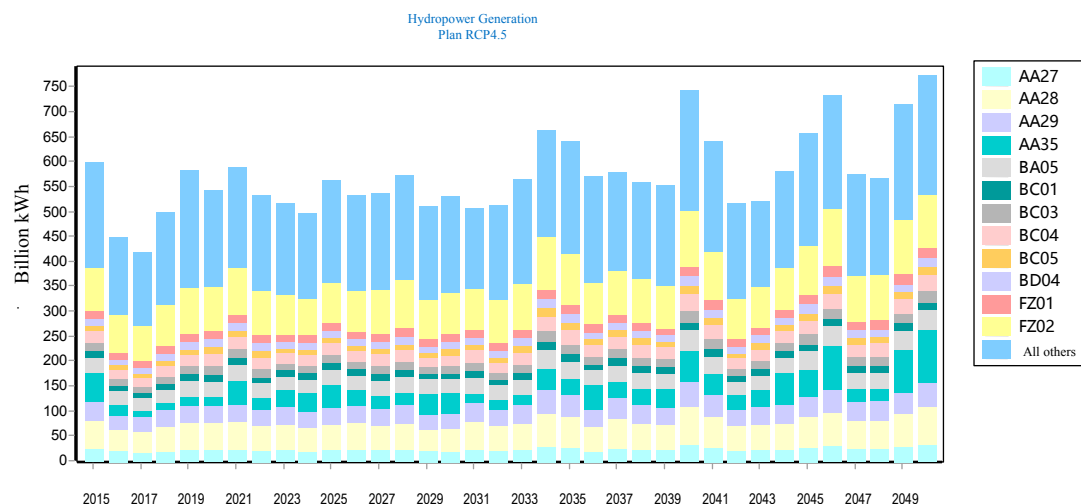


Figure 3. Electricity output under the RCP4.5 scenario. Note: The legends represent the appointed hydropower stations. The detailed code rule is shown in Appendix A, which is the same below.

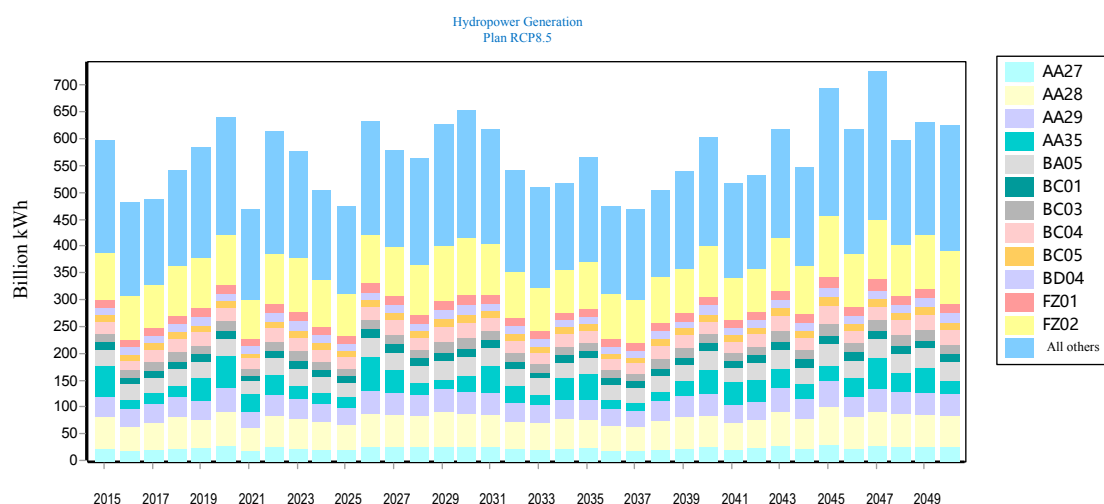


Figure 4. Hydropower generation under the RCP8.5 scenario.

5.3. Simulated Results of Main Power Stations

The top 10 large hydropower stations will still contribute to a majority of electricity output. In 2015, the total electricity generated by the 10 large hydropower stations, namely, Three Gorges, Xiluodu, Lead Plant, Wudongde, Xiangjiaba, Xiluodu, Jinping-II, Jinping-I, Gezhouba and Ertan Hydropower Stations, reached 365.3 billion kWh which comprised 61.12% of the nationwide total. Under RCP4.5 and RCP8.5 scenarios, the Ertan Hydropower Station will fall out of the top 10 list in 2030 and 2050 in terms of electricity output, but the Pubugou Hydropower Station will fill the gap. In 2030, the total electricity output of the top 10 hydropower stations will reach 317.2 billion kWh under the RCP4.5 scenario, contributing 59.71% to the total, and 390.1 billion kWh under scenario RCP8.5, contributing 59.68%. In 2050, the estimated total electricity output of the top 10 hydropower stations is 506.1 billion kWh under the RCP4.5 scenario, contributing 65.57%, and 365.4 billion kWh under the RCP8.5 scenario, contributing 58.28%.

5.4. Simulation Results of Main River Basins

Hydropower stations in Yunnan, Sichuan, Hubei and Guizhou Provinces will still contribute more than 90% to the total electricity output within the Yangtze River Basin. In 2015, the electricity outputs

in Yunnan, Sichuan, Hubei and Guizhou were 222,365, 155,994, 117,641 and 49,700 million kWh which represented 37.20%, 26.10%, 19.68% and 8.32% of the total within the Yangtze River Basin, respectively, and correspondingly and collectively accounted for 91.30%. The electricity output in each of other six provinces (i.e., Anhui, Gansu, Hunan, Jiangxi, Shaanxi and Chongqing) constituted less than 5%. In 2030, the total electricity output in the first four provinces will comprise 90.55% (RCP4.5) and 91.76% (RCP8.5) under the two scenarios; in 2050, these proportions will be 94.05% (RCP4.5) and 90.40% (RCP8.5).

5.5. Simulation Results of Main Provinces

Hydropower stations in eight river basins, namely, the Jinsha, stem stream of the Yangtze, Ya-lung, Minjiang, Wujiang, Yuanjiang, Han and Jialing Rivers, will still contribute more than 90% to the total electricity output within the Yangtze River Basin. In 2015, the electricity outputs of the eight river basins were 255,441, 102,216, 67,949, 48,205, 44,123, 32,023, 12,886 and 9760 million kWh, accounting for 42.74%, 17.10%, 11.37%, 8.06%, 7.38%, 5.36%, 2.16% and 1.63%, respectively, of the total within the Yangtze River Basin and correspondingly and collectively accounting for 53.06%. The electricity output in each of other 12 river basins (i.e., Tuojiang, Qingyijiang, Wanhe, Ba, Qingjiang, Xiangjiang, Zishui, Xinjiang, Ganjiang, Xiu, Longhe and Yulin Rivers) accounted for less than 1.5%. In 2030, the total electricity output in the eight river basins will represent 95.79% (RCP4.5) and 97.44% (RCP8.5) under the two scenarios; in 2050, these proportions will be 92.14% (RCP4.5) and 97.98% (RCP8.5).

5.6. Comparison between Two Scenarios

The two scenarios differ in electricity output. The annual average hydropower generation in 2016–2050 is 0.63% lower and changes in hydropower generation are more stable under the RCP8.5 scenario than those in the RCP4.5 scenario. Figure 5 shows the comparison between RCP4.5 and RCP8.5 scenarios in hydropower generation, which indicates that the estimated hydropower generation in 2016–2030 is generally lower in the RCP8.5 scenario than that in the RCP4.5 scenario. In 2030–2050, the RCP4.5 scenario is generally lower than the RCP8.5 scenario. The estimated annual average hydropower generation during 2016–2050 under the RCP4.5 scenario is 588,972 million kWh, whereas that under the RCP8.5 scenario is 585,270 million kWh, which is 0.63% lower than that under the RCP4.5 scenario.

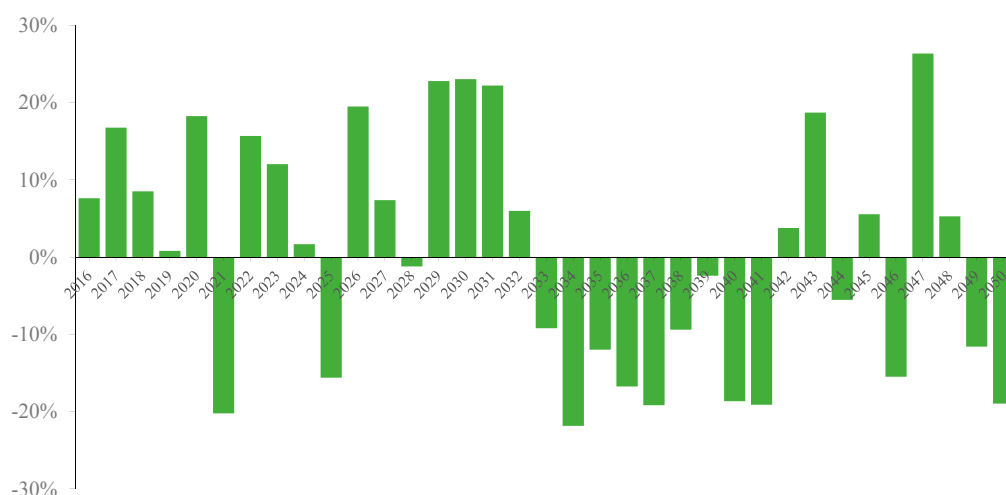


Figure 5. Relative difference in hydropower generation forecasting under the RCP8.5 scenario relative to the RCP4.5 scenario (%).

6. Discussion

The research results suggest that future climate change scenarios will affect global and Chinese water resources and will increase uncertainties in water resources. Run-off variation speed and trend under climate change scenarios (RCP4.5 and RCP8.5) will greatly vary from each region, and extreme weather may occur worldwide. Consequently, run-off in many regions may significantly increase by more than 100% or decrease by more than 60%. In China, run-off variation and its trend will greatly vary from each area, in which run-off will increase in most areas, including Yangtze and Yellow River Basins, but decline in South China; this variation and trend will even increase by more than 100% or decrease by over 60% in some areas. The results show that the trend of uneven distribution of water resources worldwide and that in China resulting from global climate change will increase together with uncertain water resource supply. The results also indicate great uncertainty in water resource supply in various areas and river basins, increased occurrence frequency of extreme water resource shortage and abundance and high possibility of affected energy supply systems in the future.

The total electricity output by hydraulic systems within the Yangtze River Basin shows a wave-like rise from 2016–2050 under RCP4.5 and RCP8.5 scenarios. Specifically, the electricity output by hydropower stations shows great fluctuations under the RCP4.5 scenario, which will first decrease and then increase, and is estimated to reach 531,219 million kWh in 2030, representing a decrease of 11.12%, but will rise notably to 771,753 million kWh in 2050, representing an increase of 29.12% over 2015. By contrast, the electricity output under the RCP8.5 scenario by covered hydropower stations within the Yangtze River Basin will steadily increase and is estimated to reach 653,615 million kWh in 2030, representing an increase of 9.35% or over, and 625,410 million kWh in 2050, representing an increase of 4.63% over 2015. Table 2 displays the specific results of comparison between the two scenarios.

Table 2. Analysis of electricity output in 2015, 2030 and 2050 under RCP4.5 and RCP8.5 scenarios.

	2015	RCP4.5		RCP8.5	
		2030	2050	2030	2050
Total electricity output (100 million kWh)	5977.07	5312.19	7717.53	6536.15	6254.10
Rate of changes in total electricity output over 2015		−11.12%	29.12%	9.35%	4.63%
Proportion of electricity output by the top 10 large hydropower stations	61.12%	59.71%	65.57%	59.68%	58.28%
Proportion of electricity output in the top four provinces	91.30%	90.55%	94.05%	91.76%	90.40%
Proportion of electricity output within the top eight river basins	95.80%	95.79%	92.14%	97.44%	97.98%

Significant fluctuations are expected in different years despite an increase in electricity output by hydraulic systems within the Yangtze River Basin in the context of future global climate change based on research findings. Such fluctuations indicate the direct effect of the uncertainty in water resource supply resulting from climate change on the sustainable development of energy systems. In the case of high temperature increases, the supply by energy systems will slightly increase, whereas such supply will first decrease under low temperature and then significantly increase, thereby increasing the vulnerability and uncertainties of hydraulic energy supply systems. Socio-economic and ecological development in the Yangtze River Basin could potentially further require clean energy supply, especially clean electricity supply. We determine high vulnerability and uncertainties in clean electricity supply in the Yangtze River Basin under climate change. Increasing hydropower plant efficiencies will be an effective strategy in reducing the impacts of climate change on clean electricity supply.

The data on future run-off variations within the Yangtze River Basin obtained through 36 climate change models in CMIP5 and CLM outputs from CLM–MOSART coupling show several fluctuations. The average of multiple climate change models or taking run-off data based on different models as data for hydropower generation research can be attempted to reduce uncertainties in future studies. This work describes and forecasts the situation of the Yangtze River Basin and its hydropower generation, but an opposite trend of changes in hydropower generation may occur in other river

basins under different climate change scenarios. Therefore, studies may aim to cover other river basins, such as the Yellow and Huaihe Rivers, to conduct comprehensive analysis and discussion of hydropower generation in China.

Acknowledgments: This work was supported by National Key R&D Program of China (2016YFA0602702) and National Natural Science Foundation (71573145, 71203120).

Author Contributions: Alun Gu and Yue Zhang conceived and designed the experiments; Yue Zhang and Wei Wang, Hui Lu performed the experiments; Alun Gu and Yue Zhang analyzed the data; Alun Gu and Yue Zhang wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Code rules of provinces or municipalities and primary tributaries of the Yangtze River in China.

Province or Municipality	Code	Primary Tributary	Code
Yunnan	A	Jinsha	A
Sichuan	B	Jialing	B
Anhui	C	Ya-lung	C
Gansu	D	Minjiang	D
Guizhou	E	Xinjiang	E
Hubei	F	Tuojiang	F
Hunan	G	Qingyijiang	G
Jiangxi	H	Wanhe	H
Shaanxi	I	Wujiang	I
Chongqing	J	Yuanjiang	J
		Bahe	K
		Hanshui	L
		Qingjiang	M
		Xiangjiang	N
		Zishui	O
		Ganjiang	P
		Xiuhe	Q
		Longhe	R
		Yulinhe	S
		secondary tributaries	Z

Appendix B

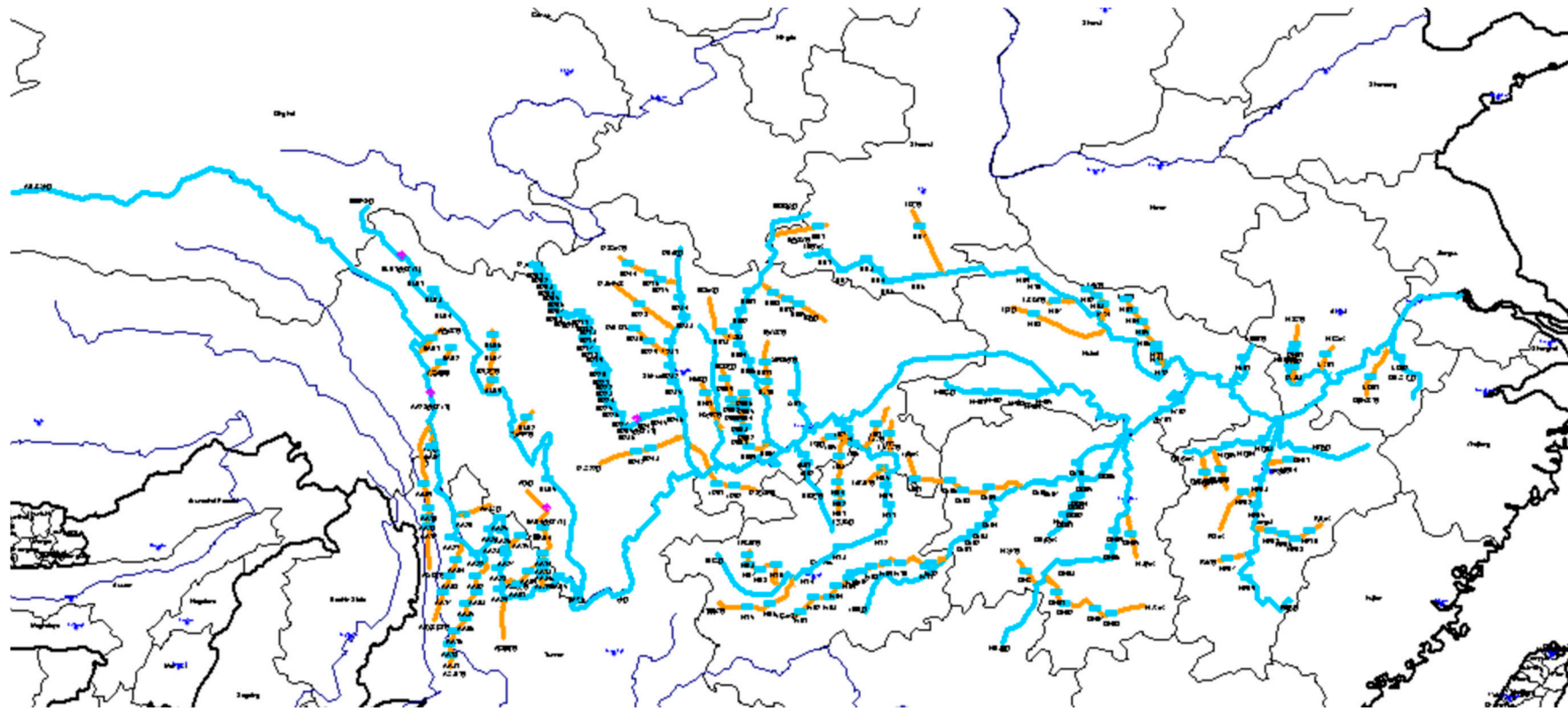


Figure A1. The Yangtze River in China and hydropower stations outlined based on the WEAP model.

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