LETTER

Water shortage risks for China’s coal power plants under climate change

X W Liao1,2,*, J W Hall1, N Hanasaki3, W H Lim1 and H Paltan4,5

1 Environmental Change Institute, University of Oxford, Oxford OX1 3QY United Kingdom
2 School of Environment and Energy, Peking University Shenzhen Graduate School, Shenzhen 518055 People’s Republic of China
3 National Institute for Environmental Studies, Tsukuba, Japan
4 School of Geography and the Environment, University of Oxford, Oxford OX1 3QY United Kingdom
5 Instituto de Geografía, Universidad San Francisco de Quito, Quito, Ecuador

* Author to whom any correspondence should be addressed.
E-mail: xiawei.liao@pku.edu.cn and lxw753951@gmail.com

Keywords: water-energy nexus, water shortage risks, hydrological modeling, coal power plants, climate change

Supplementary material for this article is available online

Abstract

China is the largest electricity producer in the world and more than 70% of its electricity is from coal-fired power plants where water is an indispensable input, primarily for cooling purposes. Water shortages could hamper coal-fired power plants productions and result in economic losses. In this study, we simulate monthly river flows in China on a 0.5° × 0.5° spatial resolution using a calibrated physically based hydrological model, H08, that incorporates human interventions during the current (1981–2014) and future period 2050s (2035–2065) under two carbon emission scenarios Representative Concentration Pathway 2.6 and 8.5. Water demands by individual power plants are calculated based on plant-level data. We define power plants as facing low-flow water risks when the monthly 10 year return low flow is projected to be below the plant’s water withdrawal requirement. We find that around 10% of China’s coal-fired power capacities face low-flow water risks from July to October (the monsoon peak in the eastern Asia), and 20% the rest of the year. Particularly in the North Grid, around 35% to 60% of its regional coal-fired power capacity is at such risks from December to June. Under climate change, low-flow amounts are expected to increase in the current dry northern China except decreasing in the northwest, which is expected to alleviate the low flow water risks facing coal power plants in China except in the Northwest Inland River Basin. In the East and South Grids, if their growing electricity demands continue depending on coal, increasing utilization rate of coal power facilities can lead to heightened demand-driven water risks.

1. Introduction

Thermoelectric power generation, which meets more than 60% of global electricity demand, uses significant volumes of water, primarily to cool steam turbines (Gleick 1994). Water withdrawn by thermoelectric power plants is responsible for over 40% and 50% of the total freshwater withdrawal in the European Union and United States respectively (United Nations World Water Assessment Programme (UN WWAP) 2014). In China, thermoelectric power plants account for over 70% of the country’s total electricity production and over 10% of the national freshwater withdrawal (Liao et al. 2016). Such close interdependency means that power provision can be exposed to and disrupted by water-related risks. For example reduced water availability and increased water temperature during low flows (Van Vliet et al. 2012) have been documented throughout the world (Mccall et al. 2016) and raised growing concerns in the energy sector.

Climate and hydrological models help us better anticipate and prepare for the future contingencies of such risks. For example, Van Vliet et al. (2012) projected a potential 6.3%–19% and 4.4%–16% capacity decrease for European and American power plants respectively during summers for the period between 2013 and 2060. Furthermore, reduction in
annual maximum potential usable capacity for global thermal power plants is projected to be 80% from 2040 to 2069 (Van Vliet et al 2016). Zhou et al (2018) estimated a similar trend by incorporating changes in water demand by thermal electric power production.

China may face pronounced challenges in this regard because of its electric power sector’s substantial and growing demands as well as its significant reliance on thermoelectric power plants that are prevalently located on inland waterways. The risks are further aggravated by China’s uneven temporal and spatial distributions of water resources (Zhang and Anadon 2013, Zhou et al 2018), as well as their mismatch with energy reserves. Figure 1 illustrates China’s 10 major river basins and 6 regional electricity grids, i.e. North, Northwest, Northeast, South, Central and East. River basins in the south (Yangtze, Pearl, Southeastern and Southwestern rivers) have larger runoffs than river basins in the north, except Songhua and Liao rivers in the northeast. Accordingly, power grids in the south (south, central and east) are more water-abundant than power grids in northern China, particularly the north and northwest. As it can be seen from figure 1, North Grid has relatively high electricity consumption and production figures, yet it is not rich in water and thus this region has been identified as facing the highest water risks for power generation in the world (Ye and Zhang 2013, Sadoff et al 2015).

Furthermore, impacted by the dynamics of the monsoon, precipitation in China demonstrates substantial intra-annual variations, which is the lowest in the winter and highest in the summer (Ye and Zhang 2013).

Zheng et al (2016) conducted a high-resolution (0.5°) quantification of China’s thermoelectric power plants’ future vulnerability to water scarcity and pointed out that it could increase in northwestern China by 2030. However, four aspects in their work can be further improved: (1) they acquired water withdrawal data from aggregate statistics whose quality can be improved by using plant-level water-using technology data; (2) water withdrawal of each geographical cell was calculated by adding up all power plants’ water withdrawals. That may overestimate the vulnerabilities because the water withdrawal of upstream power plants can be returned to the water body and reused by downstream power plants within the same half-degree geographical cell; (3) the quantification was conducted annually therefore risks on shorter timescales may be overlooked; (4) water availability data were calculated from the Variable Infiltration Capacity (VIC) hydrological model (Liang et al 1994) that does not take into account other anthropogenic water interventions, e.g. agriculture, domestic and reservoir operation, therefore water available for thermoelectric power production was overestimated.

Against this backdrop, we assess the current and future (2050s) water shortage risks (hereinafter used interchangeably with water risks) facing China’s thermoelectric power plants at a plant level and on a monthly basis. Water risks for thermoelectric power plants’ are defined as circumstances where their water availability falls short of their water demand. Water demand is calculated based on plant-level data (data types and sources are detailed in section 2.6). Monthly river flows are simulated on a 0.5°x0.5° spatial resolution with a physically based hydrological model H08, which includes human water uses. Because plants are identified individually, the return flows of cooling water are adequately accounted for within each 0.5°x0.5° cell.

2. Methods and models

2.1. Hydrological model description

We use a hydrological model H08 (Hanasaki et al 2008a,b) to simulate water available for thermoelectric power plants cooling use, which equals natural river discharge deducting agriculture and domestic withdrawals while also taking reservoir operation into account. H08 is a physical hydrological model that also explicitly expresses major modifications to water courses and water withdrawals. H08 solves the surface energy and water balance at a daily interval at 0.5°x 0.5° spacing based on the Manabe bucket model (Manabe 1969). The estimated gridded daily runoff is routed through the digital river network that represents the actual rivers in the world. During routing, water is abstracted for agricultural, industrial, and domestic water consumption, and regulated at major man-made reservoirs. H08 is one of several physical global models that incorporate such human activities. The capability, limitation, and challenges of state-of-the-art global hydrological models are well described in Hanasaki et al (2014), Bierkens (2015) and Wada et al (2017).

The H08 model consists of five primary modules: (1) The Land Surface Module calculates the energy and water balances at the land surface level, and estimates hydrological variables such as evaporation, transpiration, soil moisture, and runoff; (2) The River Routing Module transports runoff through a digital river network in order to estimate gridded river flows; (3) The Crop Growth Module estimates irrigation water requirements and (4) Water Abstraction Module represents water abstraction for other agriculture and domestic uses; (5) Finally, the Reservoir Module simulates reservoir operations. Further detailed description of these modules can be found in Hanasaki et al (2008a).

This national simulation on China is conducted on a 0.5° × 0.5° spatial resolution at a daily interval. Daily gridded global climate data of Weedon et al (2014), including surface pressure, rainfall, snowfall, wind speed, long-wave downward radiation, short-wave downward radiation, specific or relative humidity and air temperature, are used as inputs. From
here, the monthly average results are presented and analyzed.

2.2. Model calibration and validation

For calibration, a natural hydrological simulation (land surface module and river routing module) on China is conducted with 864 combinations of four key parameters, soil depth, drag coefficient, the subsurface runoff shape parameter $\gamma$ and the time constant $\tau$ for subsurface flow generation (GAMMA and TAU), from predetermined ranges (for more details see Hanasaki et al 2014). In common with other large-scale and global studies, we adopt a calibration method based on structured sampling of the parameter space, using physically plausible parameter ranges (Masood et al 2015). We used parameter values conditioned on observed land surface properties. The optimal set of parameters is estimated according to the Nash-Sutcliffe Efficiency test (Nash and Sutcliffe 1970) at each station against the monthly observational records at the 22 gauging stations from January 1981 to December 1983 (table 1). Due to lack of publicly available historical time-series river discharge data in China, we obtain river discharge data of 35 stations in China from the Global Runoff Data Centre (GRDC) (2017). However, 13 stations have (i) missing data; (ii) data that are from time periods mismatched with others; or (iii) only annual data. Furthermore, no data are available after 2000. For calibration and validation processes, we select 22 gauging stations where monthly data of the longest overlapping period, 1981–1986, are available. These 22 stations are located in six major river basins, out of 10 in total, in China as shown in figure 1 and table 1. In order to better capture low flows, the test is performed on the log transformed flows (NSE$_{\log}$). Observation data are not naturalized due to lack of reliable data of water withdrawal and flow regulation at a sub-annual interval. Such data are difficult to obtain unless in exceptionally data-rich regions. From this evaluation, the NSE$_{\log}$ of the optimal parameter set is found to be greater than zero in all 22 gauging stations as shown in table 1.

For validation, river discharge is first simulated taking irrigation and domestic water uses into account as well. The simulated monthly discharge data from 1984 to 1986 are validated at the 22 gauging stations based on NSE$_{\log}$ and NBIAS (Details see Hanasaki et al 2008b). The results are presented in table 1. According to Moriasi et al (2007), model simulation can be judged as satisfactory if NSE > 0.50 and if BIAS < 25% for streamflow. All stations met the...
Table 1. Calibration (1981–1983) and validation (1984–1986) results against monthly discharge data at 22 gauging stations using NSE\(_{\log}\) and Normalized Bias of Mean Annual Discharge (NBIAS).

| GRDC ID  | Basin  | NSE\(_{\log}\)_Calibration | NSE\(_{\log}\)_Validation | NBIAS Validation | GRDC ID  | Basin  | NSE\(_{\log}\)_Calibration | NSE\(_{\log}\)_Validation | NBIAS Validation |
|----------|--------|----------------------------|---------------------------|-----------------|----------|--------|----------------------------|---------------------------|-----------------|
| 2106 500 | SRB    | 0.523                      | 0.766                     | 0.007           | 2181 900 | YTRB   | 0.549                      | 0.288                     | 0.013           |
| 2106 600 | SRB    | 0.052                      | -0.088                    | -0.027          | 2182 050 | YTRB   | 0.179                      | 0.490                     | 0.020           |
| 2180 400 | YRB    | 0.609                      | 0.551                     | -0.030          | 2182 100 | YTRB   | 0.892                      | 0.866                     | -0.004          |
| 2180 500 | YRB    | 0.100                      | -0.062                    | 0.042           | 2182 250 | YTRB   | 0.738                      | 0.600                     | 0.016           |
| 2180 711 | YRB    | 0.426                      | 0.238                     | 0.020           | 2180 800 | HUB    | 0.213                      | -0.438                    | 0.033           |
| 2180 750 | YRB    | 0.717                      | 0.539                     | -0.058          | 2181 950 | HUB    | 0.823                      | 0.826                     | -0.036          |
| 2181 200 | YTRB   | 0.768                      | 0.705                     | 0.013           | 2181 951 | HUB    | 0.847                      | 0.440                     | -0.068          |
| 2181 300 | YTRB   | 0.649                      | 0.770                     | 0.007           | 2178 200 | SERB   | 0.877                      | 0.814                     | -0.018          |
| 2181 500 | YTRB   | 0.205                      | 0.009                     | 0.003           | 2186 800 | PRB    | 0.825                      | 0.907                     | -0.001          |
| 2181 600 | YTRB   | 0.629                      | 0.564                     | 0.002           | 2186 900 | PRB    | 0.874                      | 0.866                     | 0.002           |
| 2181 800 | YTRB   | 0.670                      | 0.560                     | 0.003           | 2186 950 | PRB    | 0.825                      | 0.559                     | -0.005          |

Criteria

- NSE\(_{\log}\) > 0  
- NSE\(_{\log}\) > 0.5  
- NBIAS < 0.25

| Criteria Station No. | Criteria Station No. | Criteria Station No. | Criteria Station No. |
|----------------------|----------------------|----------------------|----------------------|
| NSE\(_{\log}\) > 0   | 19                   | NSE\(_{\log}\) > 0.5 | 14                   |
| 0.25 < NBIAS < 0.25  | 22                   |                      |                      |

Note: SRB—Songhua River Basin; YRB—Yellow River Basin; YTRB—Yangtze River Basin; HUB—Huai River Basin; SERB—Southeast River Basin; PRB—Pearl River Basin
criteria for NBIAS. NSE_{log} agreed with the criteria for 19 of the 22 gauging stations, among which, 14 had NSE_{log} value larger than 0.5.

Data for 42 large reservoirs (e.g., location, capacity, surface area) with capacity greater than 1 cubic kilometer in China are included in the simulation. The simulated storage and release of these reservoirs are controlled by the generic reservoir operation algorithm implemented in H08. It can be seen from figure 2 that incorporating reservoir operation improves NSE_{log} performance at station 2 106 600 (Songhua River Basin) from −0.088 to 0.319 (Hydrograph is demonstrated as figure 6). It should be noted that two stations in the Yellow River Basin (2 180 500) and Huai River Basin (2 180 800) still fail the NSE_{log} test even with reservoir operation module enabled, which indicates the need to obtain and incorporate more observational data for future studies of these basins as two of the most developed basins in the world.

2.3. Future climate projections

We simulate China’s future river discharge in the 2030s (2015–2045) and 2050s (2035–2065). We use the bias-corrected meteorological forcing data from five General Circulation Models (GCMs) provided by the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP): HadGEM2-ES, GFDL-ESM2M, IPSL-CM5A-LR, MIROC5-CHRM, and NorESM1-M (Hempel et al 2013). ISI-MIP aims to quantify the uncertainty in projecting climate change impacts on water and other sectors using a minimal setting that covers uncertainties in climate models and climate scenarios. According to Mcsweeney and Jones (2016), these five ISI-MIP GCMs adequately capture the inter-quartile range of the climate uncertainties embodied in the entire Coupled Model Intercomparison Project Phase 5 models over the continental China. Two emission scenarios are selected: Representative Concentration Pathways (RCP) 2.6 and 8.5, in which the anthropogenic radiative forcing equals 2.6 and 8.5 W m\(^{-2}\) by 2100, respectively (IPCC 2014). We select these two scenarios because they correspond to low emission and high emission scenarios in the future and represent the widest range of climate outcomes.

2.4. Water demand by thermoelectric power plants

While coal and gas provide more than 95% of China’s thermoelectric power, thermoelectric power plants are used interchangeably with coal-fired power plants in this study because (1) we do not have information on gas-fired power plants in China; (2) gas-fired power generation only provides less than 4% of the thermoelectric power generation in China (China Electricity Council 2015). We exclude power plants that are located on the coast as they are likely to use sea water for cooling rather than freshwater, whose total capacity amounts to approximately 80 GW. In total, about 790 GW of inland coal-power plants are included in our evaluation.

Water use at coal-fired power plants can be quantified by multiplying their generational outputs (MWh) and their water intensity, measured as water use per unit of electricity produced (m\(^3\) MWh\(^{-1}\)). Coal power plants’ water use is used as a collective term for both water withdrawal and consumption. Water withdrawn initially by coal power plants from, but not discharged back to, the river system is defined as their water consumption (AQUASTAT 1998). Water shortage risks are evaluated comparing water availability to power plants’ withdrawal demand. Water consumption is used to calculate the return flow which is available for downstream power plants. Power plants’ generation output is determined by power plants’ capacity (MW) and the capacity factor, i.e. utilization rate, defined as the ratio of actual electricity production divided by the maximum possible electricity output of a power plant over a certain period. Different types of cooling technologies dictate coal power plants water intensities (Macknick et al 2012): Air-cooling has the least water use; open-loop cooling systems use running water and have larger water withdrawal but less water consumption compared to closed-loop cooling ones because the latter use re-circulated water. Because China’s unique dispatch mechanism tries to assure all Electricity Generation Units (EGUs) have the same capacity factor (The Regulatory Assistance Project (RAP) 2016), we assume all EGUs within the same province have the same annual capacity factor. Therefore, the current coal power plants water demands are calculated based on the provincial capacity factor in 2015. The future utilization of coal power plants in China depends on many social-economic factors, including future energy demand, capacity of new power plants built, generation and cooling technologies adopted for new plants and the decommissioning of old plants. Its estimation requires further elaborate work that is beyond the scope of this study. We introduce three simple scenarios of coal power plants’ different utilization rates in the future. Under the Business As Usual (BAU) scenario, coal power plants will have the same annual capacity factor in each province as in 2015. Under the High utilization scenario and Low utilization scenario, power plants will have 140% and 60% of the BAU capacity factor respectively. The high utilization rate is set at 140% of the current level as it reaches the maximum usable potential in some provinces, for instance in Ningxia during November and December. The low utilization rate is set at 60% of the current level accordingly. Low utilization scenario encompasses potential future scenarios where China reduces its dependence on coal and transforms to other energy sources; High utilization scenario corresponds to potential future scenarios where China’s increasing high electricity demand will still be met by coal power facilities primarily.
2.5. Water risks for coal power plants in China
We define that if the simulated monthly 10 year return low flow (monthly stream flow value that is exceeded 90% of the time in the same month) in the rivers falls short of a power plant’s water withdrawal demand, the power plant is considered to be facing water risks. Agricultural and domestic water uses are deducted from the natural river flows to determine the amount of water available for coal power plants. Coal power production has priority over manufacturing industrial water uses. Reservoir operation is also incorporated in our simulations. If there is more than one power plant located within the same geographical cell, water available for downstream power plants equals water available for upstream power plants minus the upstream power plants’ consumptive water uses.

2.6. Data
We compile the generation capacity and cooling technology of China’s over 2300 coal-fired EGUs whose aggregate capacity amounts to 870 GW (including about 80 GW on the coast), which equals to about 86.5% of the nation’s total thermoelectric power capacity in 2015. The specific steps of these simulations are as follow: (1) we compile a comprehensive dataset of China’s coal-fired EGUs from multiple sources, including Carbon Monitoring for Action (Center for Global Development 2015), World Electric Power Plants Data Base (Utility Data Institute 2015), Global Coal Plant Tracker (Global Energy Monitor 2015) and Enipedia (Davis et al 2015). Those databases contain cooling technologies information for some power plants, but with the majority being missing. (2) Same as the US Geological Survey (Diehl et al 2013), we identify individual power plants’ cooling technology with Google Earth Imagery. Closed-loop cooling towers can be visually identified. We assume power plants without such cooling towers but located close to water bodies are equipped with open-loop cooling systems, otherwise with air-cooling ones. (3) We further crosscheck the data acquired with existing information as well as individual power plant’s websites. Although water consumption intensities are reported for a number of power plants by (China Electricity Council (CEC) 2013a,b), water withdrawal intensities are not available. Therefore for consistency, the median values of water intensities, both for withdrawal and consumption, of different cooling technologies from Macknick et al (2012) in the US are used. A previous study by Zhang et al (2017) concluded that the average water intensities of Chinese coal power plants are comparable to the median values of that of coal power plants in the United States.

3. Results
3.1. Climate change impacts on China’s water resources
Figures 3(a)–(b) demonstrate the average of monthly mean stream flow and monthly 10 year return low flow respectively during the current period (1981–2014). The spatial patterns of the monthly mean flow and 10 year return low flow overlap largely. It can be seen that river basins in southern and northeastern China are endowed with relatively rich water resources. Large areas in the north and northwest have very low stream flow values.

The changes of the monthly mean stream flow and monthly 10 year return low flow between the current period and future period 2050s (2035–2065) under the RCP 2.6 scenario are demonstrated in figures 3(c)–(d) respectively. 2050s is selected as the future horizon for our analyses because (i) power plants constructed in 2020 are expected to have a 0
to 40 years life span until 2050 to 2060. (ii) There is no apparent difference in the simulated flow regimes found between the two future periods, 2030s and 2050s, or the two emission scenarios, RCP 8.5 and RCP 2.6. The reasons are because 2030s and 2050s are too close and the climatological differences between RCP2.6 and RCP8.5 become distinct after 2050. The results of ensemble mean of five ISI-MIP GCMs are demonstrated. If the value is larger than 1, then the increase in the corresponding flow values is larger than 100%. Both monthly mean flow and monthly 10 year return low flow are projected to increase significantly in most parts of Northern China except decreasing significantly in the Northwestern Inland River Basin. River flows are projected to slightly decrease in southern China.

Hydrographs of the 10 year return low flow at four selected stations in China’s four driest river basins, namely, Yellow, Huai, Hai and Northwestern Inland River Basins, that are all located in northern China, are demonstrated in figure 4. It can be seen that, overall, wetter future conditions projected by the GCMs are expected to increase the mean water availability during low flows in the four river basins (figure 4). The changing climate, at the projected time scale and for these analyzed scenarios, is not expected to alter the seasonal variability of river flows in these basins significantly. The driest month in the Huai and Northwestern Inland River Basins is January and February respectively, and May in both Hai and Yellow River Basins.

The availability and variability of China’s future river discharges simulated in this study agree with the study of Leng et al (2015) that focuses on China’s future surface water change using the VIC model that does not consider any human interventions.

3.2. Current low-flow water shortage risks for China’s coal power industry
At any given site of a power plant, if the water available during 10 year return low flow is not enough to meet the water withdrawal demand by the power plant, we consider the power plant to be facing low-flow water risks. Our results indicate that, during the current period, over 60% of the power plants (figure 5(a)), whose aggregated capacity is more than 100 GW (figure 5(b)), in the North Grid are facing low-flow water risks if surface water is the only water source available, i.e. no groundwater or reclaimed water is used (Note: coal power plants close to the coast are excluded from this study). According to China Electricity Council (2013a,b), 16.2% and 12.2% of China’s coal power plants’ current water uses are groundwater and reclaimed water respectively.

Nationally, about 30% of China’s power generation capacities face low-flow water risks in April and around 10% face low-flow water risks from July to October. These risks are concentrated during
the winter (November, December and January) and spring (February, March and April) seasons because: (1) due to the monsoon repercussions in the region, water availability is lower during winter and spring throughout the whole China; (2) electricity water demand is higher during these two seasons because households require higher electricity consumption for heating purposes.

It should be noted that although the water intensity (both withdrawal and consumption) for power generation varies by season due to different water and air temperatures, we do not take such heterogeneity into account in this study due to data limitations. During colder times, water intensity for thermoelectric power plants decreases because its cooling efficiency increases. Therefore, the differences between water risks in winter/spring seasons and summer/autumn seasons are overestimated.

We also examine the impacts of changing cooling technologies on coal power plants’ water shortage

Figure 4. Monthly 10 year return low flow regimes in China’s four driest river basins during the current period (1981–2014) and future periods, 2030s (2015–2045) and 2050s (2035–2065). The results of five ISI-MIP GCMs are shown.

Figure 5. Monthly low-flow water shortage risks for China’s regional coal power plants. (Note: dotted lines represent scenarios where all northern Grids adopt open-loop cooling systems while all southern Grids adopt closed-loop cooling systems).
risks. Dotted lines in figures 5(a)–(b) demonstrate the capacity and percentages of coal power plants facing water shortage risks in different regional Grids assuming all northern grids (North, Northwest and Northeast) adopt open-loop cooling systems while all southern regions (Central, South and East) adopt closed-loop cooling systems. It can be seen that adopting all air-cooling systems in the North Grid can reduce water shortage risks for coal power plants substantially, by almost 30% of the total capacity in April. Adopting all closed-loop cooling systems almost eliminates water shortage risks for coal power plants in the East and the South Grids.

Figure 6 indicates that China’s water stress is mainly located in northern China because of the low water availability (Zhao et al. 2018). Economic development is more advanced in the coastal regions, which is reflected by their larger installed coal power capacity. Particularly, the Bohai Sea Economic Rim and the Yangtze River Delta, where China’s capital city Beijing and financial center Shanghai are respectively located, are China’s two biggest and fastest growing urban agglomerations. They are home to 111 and 158 million people respectively, of which the urban population represents 62.5% and 69.8%. In 2016, these two regions generated over 10% and 20% of national GDP respectively (National Bureau of Statistics 2016). Water stress is high in these two regions due to concentrated population, high levels of economic activities and urbanites’ burgeoning lifestyle (Liao et al. 2019). It can be seen from figure 6 that during the current period, northern China faces the highest water risks for its power generation in April, which are particularly pronounced in the Bohai Sea Economic Rim region. The risks for southern China peak in December and mainly concentrate in the Yangtze Delta region. Such risks can be explained by the particularly high electricity demand in these two regions. There are a number of different ways to cope with such risks, including utilizing electricity imported from other regions, promoting electricity demand management within these two mega-regions as well as adopting more efficient cooling technologies.

Although closed-loop cooling systems have higher capital cost than open-loop ones, because northern China is water-scarce, closed-loop cooling systems that require relatively small water withdrawals are prevalent within the northern part of China. Water risks in northern China are mostly due to low water availability, hence cooling technologies are already employed seek to minimise water use. Power plants can also be switched to air cooling systems to reduce their water risks. However, air cooling systems result in higher energy consumption and greenhouse gas emission penalties because of their low cooling efficiency (Zhang et al. 2014). In comparison, water risks in southern China are primarily demand driven. Located at the mouth of the Yangtze River, coal power plants in the Yangtze Delta megalopolis predominantly employ open-loop cooling systems where a large amount of water is needed for power plants withdrawal.

3.3. Low-flow water shortage risks for China’s coal power industry under future climate change

As it can be seen from figure 7, under different climate change scenarios, the wetter conditions projected to the study area are expected to attenuate low-flow water risks in China’s coal power industry since water availability is widely increasing. Only in the Northwest Grid, climate change is expected to intensify low-flow water risks in the coal power industry in June and July compared to the current period unless the utilization rate of coal power facilities is lowered. An additional 5 to 10 GW of coal power facilities within this region will face the risk of not having enough water for cooling during summer months if their utilization rate is kept the same or increased.

In the East and South Grids, water shortage risks for coal power plants are expected to increase only under the High Utilization Scenarios. In other words, if the utilization rates of their coal power plants are increased, for example, under circumstances where their increasing regional electricity demands remain highly dependent on coal, their coal power plants are expected to face heightened risks of low river flows not being enough to meet their withdrawal demands, in February in the east and in March and November in the south. These power plants are threatened with potential curtailment of their production and are at the risk of not getting their cost recovered. Retrositing open-loop cooling systems to closed-loop ones in the south and east is an effective investment to reduce their corresponding water risks and potential economic losses due to power production reductions. However, these retrofits can be prohibitively expensive and further economic analysis should be carried out (Kablouti 2015, Loew et al. 2016).

In summary, if coal power plants’ utilization rate remains the same, wetter conditions brought by future climate change are expected to alleviate water shortage risks for coal power plants in most regions in China except in June and July in the Northwest Grid. Yet, if coal power plants’ utilization rates increase, additional coal power capacity in the East Grid and South Grid may be exposed to water shortage risks in February and March/November respectively.

3.4. Data uncertainties and sensitivity analysis

There are inevitable uncertainties in estimates of water consumption and withdrawal because data are often not measured or published. While the uncertainties are high, the nature of the uncertainties is unknown due to data paucity and poor quality (Peer et al. 2019). Although as mentioned in section 2.6, water withdrawal intensities are not comprehensively available in China, water consumption intensities are reported for a number of power plants by
Figure 6. (a) Low-flow water risks for coal power plants in northern China are the highest in April and (b) in southern China are the highest in December. (Note: Water Stress Index data are obtained from Zhao et al. 2018 and are only available at provincial level. The provinces included in each power grid are illustrated in the supplementary information available online at stacks.iop.org/ERL/16/044011/mmedia).

(China Electricity Council (CEC) 2013a, b). The self-reported water consumption data by Chinese coal power plants range from 30% to 8 times the values adopted in this study (table 2). We have thus conducted sensitivity analysis across the range [20%, 800%] of both water consumption and withdrawal intensity values. According to Peer et al. (2019), regional water consumption intensity of fossil-fueled power plants in the US ranges from 0.81 to 3.2 m³ per MWh, averaging at 1.5 m³/MWh. Thus the range of [30%, 800%] not only covers the dataset from China, but also covers the range documented in the US. In the absence of further information about the covariance of these uncertainties across power plants, we apply these sensitivity factors uniformly across all plants. This is likely to be conservative, as it is unlikely that
all plants will have intensities at one or other end of the range.

It can be seen from figure 8 that applying higher or lower water intensities does not change the spatio-temporal patterns of coal power plants being exposed to water shortage risks. The highest share of capacity in the North Grid is consistently facing water shortage risks in April. The national capacity facing water shortage risks in April ranges from 136 to 370 GW, occupying 17.19% to 46.79% of the national total capacity depending on different water intensities. On average, applying 30% of the water use intensities reduce 8.94% of regional capacity facing water shortage risks in an average month while applying 800% of the water use intensities leads to additional 13.29% of regional capacity facing water shortage risks in an average month.

In addition, future water availability for coal power plants is estimated by future river flows deducting water uses for agricultural and domestic purposes. While future river flows are simulated with inputs from climate models, water uses for agricultural and domestic uses are kept the same as in 2000 because those are the latest global gridded data available. Since China has set its total water use cap at 700 billion m³ in 2030 (Qin et al 2015), 1.26 times of that in 2000 (553 billion m³), we have conducted an additional sensitivity analysis applying $[-30\%, 30\%]$ of the water availability for coal power plants. As it can be seen from figure 9, 30% less water availability leads to additional 3.31% regional capacity facing water shortage risks while 30% more water availability results in 1.65% less regional capacity facing water shortage risks.
Table 2. Percentile figures of self-reported water consumption data by Chinese coal-power plants (China Electricity Council (CEC) 2013a, China Electricity Council (CEC) 2013b).

| Cooling Technology | Water consumption intensity (m$^3$/MWh$^{-1}$) |
|--------------------|-----------------------------------------------|
|                    | Q5    | Q25   | Q50   | Q75   | Q95   | This study |
| Closed-loop        | 0.60  | 2.20  | 2.52  | 3.00  | 5.42  | 1.87      |
| Open-loop          | 0.16  | 0.39  | 0.51  | 1.00  | 3.06  | 0.39      |
| Air cooling        | 0.22  | 0.43  | 0.50  | 0.59  | 2.48  | 0.32      |

Note: Q5 refers to 5th percentile; Q5 and Q95 figures are used as the minimum and maximum range to eliminate outliers. For closed-loop cooling systems, the maximum water intensities for sensitivity analysis are kept at 300% of the values adopted in this study according to the Q95 value for closed-loop cooling systems.

Figure 8. Sensitivity analyses on water use intensities.

4. Discussion

4.1. Vulnerability to cooling water shortage of China’s thermoelectric power plants

China is vulnerable to the effects of low river flows leading to cooling water shortages for thermoelectric power plants, with new plants continuing to be built on inland waterways. Through a comprehensive modelling exercise we have identified the seasonality and geographical location of these risks. By allocating power plants and their associated water withdrawals to specific waterways and accounting for return flows from cooling systems we have been able to improve upon previous estimates, whilst also conducting sensitivity analysis to explore key uncertainties. Risks are greatest in the north of the country where we have found that 35% to 60% of its regional coal-fired power capacity is threatened by cooling water shortage during months of low flow from December to June. In contrast, although water resources are
abundant in the southern grids (south, central and east), around 20% of coal power plants still face water shortage risks at certain months of the year because they often use open-loop cooling systems that require significant volumes of water withdrawal. Retrofitting cooling technologies with air cooling in the north and closed-loop cooling in the south is able to substantially reduce such abovementioned risks. Furthermore, transforming the power sector to low-carbon energy sources and reducing the capacity factor of coal power plants accordingly is also able to realize such objectives.

4.2. Impacts of climate change on thermoelectric power plants’ vulnerability to cooling water shortage in China

Scenario analysis using climate models reveals that climate change may alleviate impacts of low flows in the coal power sector in most regions and most seasons in China due to wetter conditions, especially in the northern grids. Except in the northwest, climate change is expected to reduce river flows and therefore aggravate thermoelectric power plants’ vulnerability to cooling water shortages. It should be noted that rising global temperatures are also thought to importantly impact regional high flows and floods and Hu et al (2015) pointed out that China’s power infrastructures are also vulnerable to flood risks, which is likely to increase under climate change (Paltan et al 2018). Apart from water availability and variability, climate change could also affect the power sector’s water uses and risks through other mechanisms: warmer stream flows and increased electricity demand due to warmer weather are two prominent examples. Van Vliet et al (2012), (2016) found that thermoelectric power plants’ usable capacity can be reduced due to higher stream flow temperature combined with regulations on power plant’s discharge water temperature. Moreover, possible warmer weather and increased heat waves
will increase household electricity demands for air conditioning. All of these effects contribute to potentially heightened water risks in the electric power sector.

4.3. Improving the power sector’s resilience towards water shortage risks under climate change

There are several ways to improve the resilience of China’s coal power sector towards future water shortage risks under climate change. First, coal power plants are encouraged to utilize unconventional water sources. It should be noted that, in this study, we assumed surface water is the only available water source for inland coal power plants. Therefore we have overestimated the current water risks because other water sources could also be utilized. For example, thermoelectric power plants in the north commonly rely on ground water and reclaimed water from industrial and municipal wastewater. However, utilization of groundwater by newly built coal power plants has been outlawed since 2004 (National Development and Reform Commission of China 2004). Using reclaimed water incurs higher cost. Our study lays a foundation for further comparisons between curtailing power production due to surface water shortages and using reclaimed water. In the south, it has also been reported that, due to drought situations, many power plants with open-loop cooling systems have faced water shortage problems (China Electricity Council (CEC) 2012).

Secondly, retrofitting cooling technology is able to reduce water shortage risks significantly. Adopting air cooling technology in the northern grids and closed-loop cooling systems in the relatively water-abundant southern grids are able to reduce potential water shortage risks for coal power plants. However, as indicated by previous studies (Zhang et al 2014), closed-loop cooling systems and air cooling systems incur higher costs compared to open-loop cooling systems and closed-loop cooling systems respectively due to lower efficiency and larger land occupation.

Thirdly, this study shows that, if China’s growing electricity demands continue to rely on coal, coal-fired power plants might encounter higher water risks in the northwest, south and east, in the future. As most renewable energies (i.e. Solar PV and Wind) require negligible amount of water for on-site use, transforming the electric power sector to low-carbon sources is able to reduce the water use in China’s electric power sector (Liao and Hall 2018).

4.4. Interregional transfers of water shortage risks for coal power plants

It should be noted that while this study shows that water risks for coal power generation is particularly dire in the North and Northwest Grids, previous work has pointed out that, electricity production as well as its embodied water consumption in those regional grids has been transmitted to support the relatively developed coastal regions in the east (Zhang et al 2017, Liao et al 2018). Similar to the case of some basin in the US (Wang et al 2017), water shortages in the northwest of China can engender impacts beyond its boundaries on electricity-consuming activities, from household to industrial uses, in the more developed and populated regions. Such trans-boundary effects would magnify with China’s ongoing efforts on building more electricity transmission infrastructures and increasing the electricity sector’s connectivity (National Energy Administration of China 2014, National Development and Reform Commission of China 2016).

4.5. Limitations and future direction

Last but not least, this study has data limitations in two aspects: first, we calibrate the hydrological model against observational data in six basins in China, out of ten, and use default parameters for the remaining four basins where observational data are lacking. While it is a common practice when gauged data are not available, further calibrations should be done for these four basins when observational data are available; secondly, while we use water intensity data for coal power productions in the US because water withdrawal intensity data are not available in China, Peer et al (2019) showed that there are huge regional variations in water consumption intensities for coal power productions in the US and, besides cooling technologies, they are also heavily affected by local climatic conditions and other factors. Jiang and Ramaswami (2015) pointed out the significant seasonality of coal power plants’ water intensities from field data of 19 coal-fired power plants in Shandong, China. Future studies should be carried out to better quantify coal power productions’ water intensities, which could benefit refining the results of this study.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

This article is part of a project that has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie Grant Agreement No. 681228. It has also received funding from China Scholarship Council—Oxford University Scholarship (Grant No. 201406010349).

Competing interests

The authors declare no competing interests.
References

AQUASTAT 1998 AQUASTAT Definitions (FAO: Rome, Italy)

Bierkens M F P 2015 Global hydrology 2015: state, trends, and directions Water Resour. Res. 51 4923–47

Center for Global Development 2015 Carbon Monitoring for Action (Washington D.C. Center for Global Development)

China Electricity Council (CEC) 2012 Guodian Fengcheng Power Plant Solve the problem for ‘cooling water’ (In Chinese) (http://www.cec.org.cn/hangyeguangjiao/fadianxinxi/ 2012-04-17/85099.html)

China Electricity Council (CEC) 2013a National 600 Mw Scale Thermal Power Unit Benchmarking and Competition Dataset (in Chinese) (China Electricity Council: Beijing, China)

China Electricity Council (CEC) 2013b National 300 Mw Scale Thermal Power Unit Benchmarking and Competition Dataset (in Chinese) (China Electricity Council: Beijing, China)

China Electricity council 2015 2015 detailed electricity statistics Beijing, China

Davis C B, Chmieliauska A, Dijkema G P J and Nikolic I 2015 Enipedia, Energy & Industry group, Faculty of Technology Policy and Management, TU Delft Delft, The Netherlands

Diehl T H, Harris M A, Murphy J C, Hutson S S and Ladd D E 2013 Methods for estimating water consumption for thermoelectric power plants in the United States scientific investigations report 2013–5188 US Department of the Interior US Geological Survey

Gleck P H 1994 Water and Energy Annu. Rev. Energy Environ. 19 267–99

Global Energy Monitor 2015 Global Coal Plant Tracker July 2015 (https://encoal.org/global-coal-plant-tracker/)

Hanasaki N, Kanae S, Oki T, Masuda K, Motoya K, Shiraikawa N, Shen Y and Tanaka K 2008a An integrated model for the assessment of global water resources – part 1: model description and input meteorological forcing Hydrol. Earth Syst. Sci. 12 1007–25

Hanasaki N, Kanae S, Oki T, Masuda K, Motoya K, Shiraikawa N, Shen Y and Tanaka K 2008b An integrated model for the assessment of global water resources – part 2: application and assessment Hydrol. Earth Syst. Sci. 12 1027–37

Hanasaki N, Saito Y, Chaiyasaen C, Champathong A, Ekkawatpanit C, Saphaokham S, Sukhapunnaphan T, Sumdin S and Thongduang J 2014 A quasi-real-time hydrological simulation of the Chao Phraya river using meteorological data from the Thai meteorological department automatic weather stations HydroIt. Res. Lett. 8 9–14

Hempel S, Frieler K, Warszawski L, Schewe J and Piontek F 2013 A trend-preserving bias correction – the ISI-MIP approach Earth Syst. Dynam. 4 219–36

Hu X, Hall J W, Shi P and Lim W H 2015 The spatial exposure of the Chinese infrastructure system to flooding and drought hazards Nat. Hazards 80 1083–118

IPCC 2014 Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change Climate Change 2014: Synthesis Report ed C W Team, R K Pachauri and I A Meyer (Geneva, Switzerland: IPCC) 151 p

Jiang D and Ramaswami A 2015 The ‘thirsty’ water-electricity nexus: field data on the scale and seasonality of thermoelectric power generation’s water intensity in China Environ. Res. Lett. 10 024015

Kahilouti G 2015 Cost of water use: a driver of future investments into water-efficient thermal power plants? Aquat. Procedia 5 31–43 (September 2014)

Leng G Y, Tang Q H, Huang M Y, Hong Y and Ruby L L 2015 Projected changes in mean and interannual variability of surface water over continental China Sci. China Earth Sci. 58 739–54

Liang X, Lettenmaier D P, Wood E F and Burges S J 1994 A simple hydrologically based model of land surface water and energy fluxes for generic circulation models J. Geophys. Res. 99 14415–28

Liao X and Hall J W 2018 Drivers of water use in China’s electric power sector from 2000 to 2015 Environ. Res. Lett. 13 094010

Liao X, Hall J W and Eyre N 2016 Water in China’s thermoelectric power sector Global Environ. Change 41 142–52

Liao X, Zhao X, Hall J W and Guan D B 2018 Categorising virtual water transfers through China’s electric power sector Appl. Energy 226 252–60

Liao X, Zhao X, Jiang Y, Liu Y, Yi Y and Tilloston M R 2019 Water footprint of the energy sector in China’s two megalopolises Environ. Modell. 391 9–15

Loew A, Jaramillo P and Zhai H 2016 Marginal costs of water savings from cooling system retrofits: a case study for Texas power plants Environ. Res. Lett. 11 104004

Macknick J, Newmark R, Heath G and Hallett K C 2012 Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature Environ. Res. Lett. 7 045802

Manabe S 1969 Climate and the ocean circulation. 1. The atmospheric circulation and the hydrology of the Earth’s surface Mon. Weather Rev. 97 739–74

Masood M, Yeh P, Hanasaki N and Takeuchi K 2015 Model study of the impacts of future climate change on the hydrology of Ganges-Brahmaputra-Meghna basin Hydro. Earth Syst. Sci. 19 747–70

Mccall J, Macknick J and Hillman D 2016 Water-related Power Plants Curtailments: An Overview of Incidents and Contributing Factors (Golden, CO: National Renewable Energy Laboratory)

Mcsweney C F and Jones R G 2016 How representative is the spread of climate projections from the 5 CMIP5 GCMs used in ISI-MIP? Clim. Serv. 1 24–29

Moriass D N, Arnold J G, Van Liew M W, Bingner R L, Harmel R D and Veith T L 2007 Model evaluation guidelines for systematic quantification of accuracy in watershed simulations Trans. ASABE 50 885–900

Nash J E and Sutcliffe J V 1970 River flow forecasting through conceptual models part I – A discussion of principles J. Hydrol. 10 282–90

National Bureau of Statistics 2016 Statistical Yearbook of China 2016 (Beijing, China: China Statistics Press)

National Development and Reform Commission of China 2004 Requirements on the Planning and Construction of Coal Power Plants (in Chinese) (http://www.nea.gov.cn/2012-01/04/c_131262a.html)

National Development and Reform Commission of China 2016 13th Five-Year Planning of the Electric Power Sector (2016-2020) Beijing, China

National Energy Administration of China 2014 List of twelve electricity transmission corridors for air pollution control to be approved by the National Energy Administration Beijing, China

Paltan H, Allen M, Haustein K, Fuldauer L and Dadson S 2019 A global assessment of the water embedded in the US electricity system Environ. Res. Lett. 14 084014
Qin Y, Curmi E, Kopec G M, Allwood J M and Richards K S 2015 China's energy-water nexus assessment of the energy sector's compliance with the 3 Red Lines industrial water policy Energy Policy 82 131–43
Sadoff C W et al 2015 Securing Water, Sustaining Growth: Report of the GWP/OECD Task Force on Water Security and Sustainable Growth (Oxford, UK: University of Oxford)
The Global Runoff Data Centre 2017 River Discharge Data. Global Runoff Data Centre (Germany: Koblenz, Federal Institute of Hydrology (BfG))
The Regulatory Assistance Project (RAP) 2016 Issues in China power sector reform: generator dispatch Beijing, China
United Nations World Water Assessment Programme (UN WWAP) 2014 The united nations world water development report 2014 Water and Energy Paris, France
Utility Data Institute 2015 Platts Energy InfoStore World Electric Power Plants Database (http://platts.com)
Van Vliet M T H, Wiberg D, Leduc S and Riahi K 2016 Power-generation system vulnerability and adaptation to changes in climate and water resources Nat. Clim. Change 6 375–80
Van Vliet M T H, Yearsley J R, Ludwig F, Vögele S, Lettenmaier D P and Kabat P 2012 Vulnerability of US and European electricity supply to climate change Nat. Clim. Change 2 676–81
Wada Y et al 2017 Human-water interface in hydrological modeling: current status and future directions Hydrol. Earth Syst. Sci. 21 4169–93
Wang R, Zimmerman J B, Wang C, Vivanco D F and Hertwich E G 2017 Freshwater vulnerability beyond local water stress: heterogeneous effects of water-electricity nexus across the continental United States Environ. Sci. Technol. 51 9899–910
Weedon G P, Balsamo G, Bellouin N, Gomes S, Best M J and Viterbo P 2014 The WFDEI Meteorological Forcing Data Set: WATCH Forcing Data methodology applied to ERA-Interim reanalysis data Water Resour. Res. 50 WR015638
Ye W H and Zhang Y 2013 Environment Management (3rd Version) (In Chinese) (Beijing: China Higher Education Press)
Zhang C and Anadon L D 2013 Life cycle water use of energy production and its environmental impacts in China Environ. Sci. Technol. 47 14459–67
Zhang C, Anadon L D, Mo H, Zhao Z and Liu Z 2014 Water-carbon trade-off in China's coal power industry Environ. Sci. Technol. 48 11082–9
Zhang C, Zhong L J, Liang S, Sanders K T, Wang J and Xu M 2017 Virtual scarce water embodied in inter-provincial electricity transmission in China Appl. Energy 187 438–48
Zhao X, Li Y, Yang H, Liu W, Tillotson M, Guan D, Yi Y and Wang H 2018 Measuring scarce water saving from interregional virtual water flows in China Environ. Res. Lett. 13 054012
Zheng X, Wang C, Cai W, Kummu M and Varis O 2016 The vulnerability of thermoelectric power generation to water scarcity in China: current status and future scenarios for power planning and climate change Appl. Energy 171 444–55
Zhou Q, Hanasaki N, Fujimori S, Yoshikawa S, Kanae S and Okadera T 2018 Cooling water sufficiency in a warming world: projection using an integrated assessment model and a global hydrological model Water 10 872