

Water Scarcity Assessment of Hydropower Plants in China under Climate Change, Sectoral Competition, and Energy Expansion

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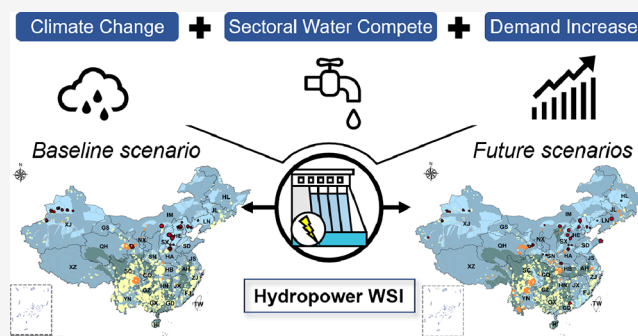
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ABSTRACT: Hydropower plays a pivotal role in low-carbon electricity generation, yet many projects are situated in regions facing heightened water scarcity risks. This research devised a plant-level Hydropower Water Scarcity Index (HWSI), derived from the ratio of water demand for electricity generation to basin-scale available runoff water. We assessed the water scarcity of 1736 hydropower plants in China for the baseline year 2018 and projected into the future from 2025 to 2060. The results indicate a notable increase in hydropower generation facing moderate to severe water scarcity ($HWSI > 0.05$), rising from 10% in 2018 to 24–34% of the national total (430–630 TWh), with a projected peak in the 2030s–2040s under the most pessimistic scenarios. Hotspots of risk are situated in the southwest and northern regions, primarily driven by decreased river basin runoff and intensified sectoral water use, rather than by hydropower demand expansion. Comparative analysis of four adaptation strategies revealed that sectoral water savings and enhancing power generation efficiency are the most effective, potentially mitigating a high of 16% of hydropower risks in China. This study provides insights for formulating region-specific adaptation strategies and assessing energy-water security in the face of evolving environmental and societal challenges.

KEYWORDS: water scarcity, hydropower, climate change, adaptation, China



1. INTRODUCTION

Hydropower is recognized as a backbone of low-carbon electricity generation, serving as a viable alternative to fossil fuels. Currently, hydropower produces about 4.5 PWh of electricity, supplying one-sixth of global energy use per year, and the number is expected to double by the mid of this century.¹ Hydropower also plays a critical role in enhancing energy security. Reservoir hydropower plants with low operational costs and large storage capacities are an affordable source of flexibility in the electricity system, compensating for fluctuations in supply from renewable energy such as wind and solar photovoltaics.² The imperative of reaching net-zero emissions globally calls for a huge increase in hydropower ambitions to deliver a clean and reliable source of backup energy.³

As one of the most touted solutions to the climate crisis, hydropower itself is now facing rising water scarcity risks. Hydropower sector relies upon water resources of substantial and predictable volume.⁴ Climate change induces changes in precipitation, evaporation, and runoff at various spatial scales, which increases the likelihood of heat waves and droughts and disrupts the stability of water resources.^{5,6} Water scarcity limits the electricity generation capacity of hydropower plants,⁷ and it is projected that global hydropower capacity would decrease

by a maximum of 10–17% per month due to declining flows by the 2050s.⁸ To fill the demand gap caused by reduced hydropower generation, local governments may shift the electricity generation mix toward fossil fuels, which increases carbon emissions and hinders the net-zero target. It is estimated that one standard deviation increase in water scarcity results in 15% expansions in natural gas generation and pollution emission in the US.⁹ Disruptions in hydropower generation due to water scarcity are also sources of social and economic risk. In 2022, heatwave dried up Sichuan Province in China, where hydropower takes 80% of the province's total power capacity. The local government issued an industrial power rationing plan, which led to cascading output losses through supply chain networks.¹⁰ In this context, it is crucial to identify water scarcity risks of hydropower projects and implement targeted adaptation strategies to ensure water–energy security.

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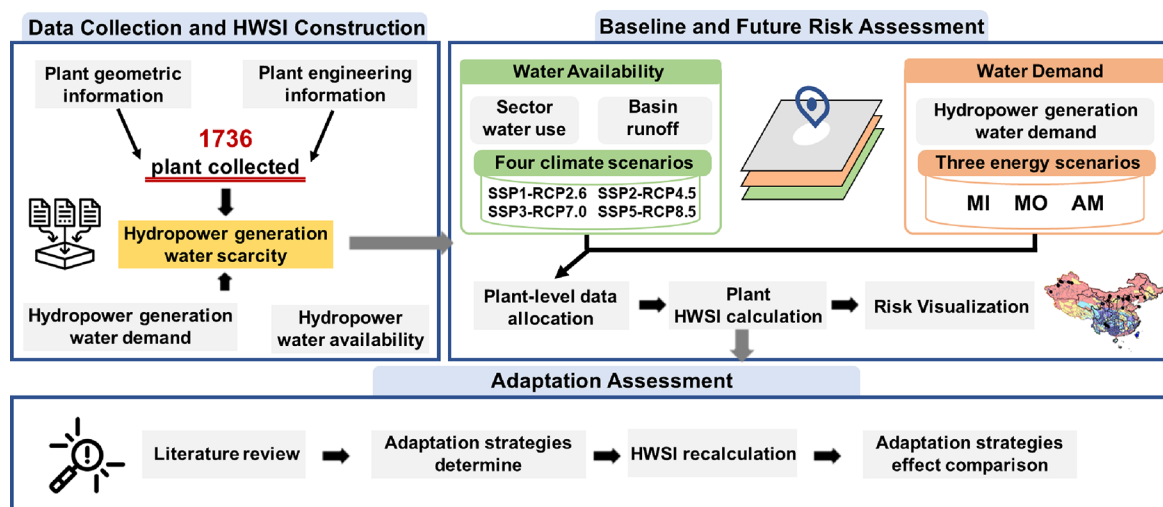


Figure 1. Conceptual framework of the three segments involved in this study.

Moreover, global water demand has sextupled in the past century, and the competition between sectoral water uses further complicated water scarcity risks in hydropower sectors. In regional water management, water usage for the purpose of hydropower generation is often considered lower in priority compared to agricultural and domestic sectors.¹¹ It is estimated that about 54% (507 GW) of the world's hydropower capacity is currently facing competition from the irrigation sector.¹² Sectoral water-use competition will continuously grow in the future.¹³ By 2030, global agricultural and industrial water demand is projected to increase by 22 and 32% above the current levels, especially in Eastern Asia countries like China where the growth rate is estimated to reach a high of 35%.¹⁴ Therefore, we may underestimate the water scarcity risks of hydropower without characterizing sectoral water competition at a finer spatial scale.¹⁵

Previous studies have employed modeling approaches to predict future water scarcity risks of hydropower projects.^{8,16} Their results showed that hydropower plants in regions where future streamflow is expected to decrease (e.g., in South America, Europe, and Asia) are anticipated to experience reductions in hydropower capacity. Each hydropower plant exhibits heterogeneity in vulnerability to water constraints due to variations in installed capacity and generation schedule. However, plant-level water scarcity analysis is still rare, largely due to the lack of reliable full plant portfolio and fine-scale available water resource data. In addition, water-use competition from other sectors was always not incorporated in these studies, which also leads to large uncertainty in the analysis of hydropower risks. An integrated approach that delineates the impacts of climate change, plant-by-plant water demand, and sectoral water-use competition would allow a more accurate understanding of future water scarcity risks faced by hydropower projects.¹⁷ Meanwhile, studies examining the effectiveness of adaptation strategies are mainly focused on an engineering perspective, such as improving power generation efficiency or switching to other types of renewable energies as alternatives, lacking region-specific design and feasibility tests.^{18,19} Hence, there is an urgent need for modeling and comparing available adaptation options in the local context to enable authorities to make well-informed decisions.

To fill these gaps, in this study, we devised a plant-level Hydropower Water Scarcity Index (HWSI) to assess the risks

of hydropower generation reduction due to water scarcity. The HWSI is derived as the ratio of water demand for electricity generation to basin-scale available runoff water. Water demand originates from hydraulic engineering consideration and refers to the water resources required to drive the turbines for electricity generation. Focusing on China, we evaluated the HWSI of 1736 hydropower plants for the baseline year 2018 and projected into the future from 2025 to 2060, considering the influence of climate change, sectoral water-use competition, and energy expansion. Hydropower is the largest renewable energy source and second after coal in China, accounting for about 16% of the country's annual electricity generation.²⁰ However, hydropower in China has already felt the noticeable impacts of climate change and water-use competition among various sectors. Addressing water scarcity risks of hydropower projects can offer essential insights for relevant strategies in the advancement of hydropower both within China and globally.

2. METHODS AND MATERIALS

2.1. Hydropower Plant Inventory. This study selects China as the case, aimed to identify the present and midterm future risks associated with inadequate water supply in hydropower generation. Figure 1 shows our conceptual framework. In this first step, we compiled a comprehensive inventory of 1736 hydropower stations in China with detailed technical parameters. Then, Hydropower Water Scarcity Index (HWSI) was developed and calculated based on the water demand for plant-level electricity generation and river basin available runoff water. In the second step, we selected 2018 as the baseline and evaluated the HWSI of hydropower plants in China. We then projected it into future scenarios from 2025 to 2060, comprising four climate change scenarios and three energy scenarios. In the final stage, we evaluated the effectiveness of four feasible adaptation strategies, considering their feasibility in different river basins.

The inventory contains both run-of-river and reservoir-storage plants, with each type representing 783 (45%) and 953 (55%) of the total, respectively. Both geographical and engineering data for each plant are provided, such as latitude, longitude, installed capacity, designed water head (the height difference between intake and discharge points), and historical annual electricity generation (2014–2018). It was compiled

based on multiple data sources including the Chinese Hydropower Data set²¹ and the Global Reservoir and Dam (GRAND) reservoir data set.²² The collected plants contribute to approximately 85% of China's total installed hydropower capacity (280 GW) and more than 95% of the annual hydropower generation (1170 TWh). The study excluded pumped-storage hydropower stations because they typically generate electricity by pumped water during times of abundant water resources. See Figure S1 for the map of plant locations.

2.2. Hydropower Water Scarcity Index. We devised a Hydropower Water Scarcity Index (HWSI) to assess water constraints on a plant-by-plant basis within hydropower facilities. This index is developed by adapting the Criticality Ratio approach, also known as the withdrawal-to-availability ratio,²³ and incorporating a water scarcity footprint methodology.²⁴ To calculate HWSI, we first need to determine WTA, defined as the ratio between the water demand for hydropower electricity generation and the water availability (eq 1). The WTA ratio is not linearly related to the risk of water scarcity since the probability cannot exceed 1. To address this, we employed a logistic function (eq 2) to transform the WTA to HWSI, allowing it to exhibit continuous values ranging from 0.01 to 1. A key differentiation in quantifying water scarcity risks of hydropower plants from prior studies lies in substituting water withdrawal with water demand. Drawing from thresholds set in earlier studies (see details in Figure S2), hydropower water scarcity is set into three levels based on the HWSI values: low scarcity (0–0.05), moderate scarcity (0.05–0.2), and severe scarcity (0.2–1).

$$WTA_i = \frac{WD_i}{WA_i} \quad (1)$$

$$HWSI_i = \frac{1}{1 + e^{-6.4 \times WTA_i \times ((1/0.01) - 1)}} \quad (2)$$

In this study, water demand for hydropower plants is defined as the amount of water required to produce a certain quantity of electricity under ideal or theoretical conditions. This concept originated from hydraulic engineering, defined as the volume of streamflow needed to drive turbines for electricity generation. We based our estimation of the water demand of hydropower plants on eq 3, derived from a widely used method for calculating regional hydropower potential.⁸

$$WD_i = \frac{P_{hy}}{H \times g \times \eta \times \rho_w} \quad (3)$$

where P_{hy} denotes the annual power generation of hydropower plants (kWh), H denotes the water head of the hydropower plant (m), g denotes the acceleration due to gravity (m/s^2), η denotes the efficiency of the hydropower generation process, and ρ_w denotes the density of water (kg/m^3). The WD, derived from this equation, corresponds to the water demand to fulfill the targeted hydropower generation for the particular year. Provincial disparities in hydropower technology were illustrated by employed provincial-scale hydropower generation efficiency.²⁵

Water availability in the study is determined based on basin runoff, sectoral water use within the basin, and environmental flow, a methodology widely adopted in prior research.^{26,27} To assess the water scarcity risks associated with hydropower generation at a high spatial resolution, we computed the water availability of each hydropower station at the third-order basin

scale. The basin boundary map was obtained from *HydroSHEDS* data²⁸ with a grid resolution of 15 arc-seconds. The formula (eq 4) for deriving plant water availability is presented below:

$$WA_i = \text{Runoff}_i - \left(E + \sum WU_{s,i} \right) \quad (4)$$

where Runoff denotes the basin runoff (m^3), E denotes the environmental flow (m^3), and WU denotes the water use by various sectors within the basin (m^3). s denotes specific water-use sector involved in the research; i denotes the corresponding basin where the hydropower plant is located. Basin runoff was calculated by first acquiring the grid runoff data from the CNRDv1.0 data set, which has been validated for its effective simulation of regional runoff in China.²⁹ Subsequently, we aggregated the CNRDv1.0 runoff data for the year 2018 to serve as the baseline scenario. The environmental flow was set at 60% of the basin runoff, a range typically established between 40 and 80% in previous studies.^{23,30} Water use of agricultural, industrial, and domestic sectors was individually quantified at the basin scale. Equation 5 displays methods for calculating water use of each sector:

$$WU_{s,m,i} = SWI_{s,m,i} \times SWB_{s,i} \quad (5)$$

where $SWI_{s,m,i}$ denotes water-use intensity of sector s in province m where basin i is located. Different water intensity indices were used for three sectors: (1) Agriculture: water use per unit area in agricultural irrigation (m^3/m^2), (2) Household: urban and rural per capita water use (m^3 per capita), and (3) Industry: water use per unit of industrial GDP (m^3/Yuan). These water intensity indices are obtained from China Water Resource Bulletin.³¹ SWB denotes corresponding basin-level sectoral activities, i.e., irrigation land area, population, and industrial GDP. To extract basin agricultural land area data, we leveraged the China Land Cover Data set (CLCD), the primary Landsat-derived annual land cover product for China.³² CLCD provides 30 m resolution annual land cover information and historical dynamics in China from 1990 to 2019. To estimate the basin-level population, we used the Gridded Population of the World database (GPWv4) gridded at a 30 arc-second resolution and distinguished between urban and rural populations based on city statistical yearbooks.³³ To estimate the industrial GDP, we utilized geographic location information and output value data of registered enterprises, obtained from the National Bureau of Statistics of China.³⁴ We then aggregated enterprise-level industrial GDP to the basin scale. The data sources for the aforementioned methods are outlined in Table S1.

2.3. Future Scenario Projections. To decouple the complex impacts of the future climate change, socio-economic development, and net-zero targets, we used three energy transition scenarios and four climate scenarios to forecast the future HWSI of the power plants. For the future total energy demand and energy structure, we designed three energy scenarios, following the 2022 World Energy Outlook published by International Energy Agency.³ Three scenarios, Ambitious (AM), Moderate (MO), and Mild (MI) predict future hydrological electricity demand from a high-to-low quantity by 2050 in China, respectively. In AM, the annual growth rate of electricity demand is projected to be 2.8% before 2030, which is expected to slow down afterward. By 2060, the expected annual electricity demand is estimated to reach 2870 TWh, with hydropower accounting for approximately 13%. In

MO, the annual growth rate of electricity demand is expected to be 2.4% before 2030, and the projected electricity generation is set to reach 2550 TWh, with the proportion of hydropower to be 10% by 2060. In MI, the annual growth rate of electricity demand will be about 2% by 2030, and total electricity generation will reach 2300 TWh by 2060 with hydropower taking up about 10%.

In addition, we have made the following assumptions when calculating the hydropower generation at the plant scale: (1) Provincial hydropower expansion rate: we assumed that 70% of China's hydropower production growth will be concentrated in eight southern provinces, considering their natural endowments and Chinese policy priorities, which is aligned with trend predictions from prior studies.²⁰ (2) New hydropower installed capacity: we have categorized the future electricity generation into two segments: the portion contributed by existing hydropower plants and that which will be generated by newly constructed facilities, aligning with "China's Hydropower Development Plan". (3) Hydropower plant retirement: the life span of hydropower stations is set based on the "Hydropower Engineering Retirement Standards" released by the Chinese government. (4) Maximum operating time: the maximum allowable operating time for hydropower stations is capped at 7000 h. For specific details, refer to the [Supporting Information](#), Text 1.4. [Equations 6](#) and [7](#) present the calculation process.

$$\text{AHG}_{p,\text{year}} = (\text{AHG}_y - \text{AHG}_{2018}) \times \frac{\text{AHG}_{p,2018}}{\text{AHG}_{x,2018}} \times \text{GR}_x \quad (6)$$

$$\text{HG}_{y,i} = \text{HG}_{2018,i} \times \frac{\text{AHG}_{p,y}}{\text{AHG}_{p,2018}} \times \frac{\text{IC}_{\text{exist},y}}{\text{IC}_{\text{total},y}} \quad (7)$$

where AHG denotes total annual hydropower generation (KWh), *p* denotes province, *y* denotes the simulated year, GR denotes hydropower generation growth rate, *x* denotes the type of growth rate (core/minor), HG denotes hydropower electricity generation (KWh) of a single plant *i* in the particular year to estimate, IC_{exist} denotes exist installed capacity, and IC_{total} denotes total installed capacity (KW).

Then, to predict regional water availability, four climate scenarios within the Coupled Model Intercomparison (CMIP6) Project framework (SSP1-RCP2.6, SSP2-RCP4.5, SSP3-RCP7.0, and SSP5-RCP8.5) were obtained to estimate future basin runoff. These scenarios are widely employed to represent different socio-economic development paths and climate change policies and assess possible climate change impacts. SSP1-RCP2.6 assumes strong global climate action with large-scale emission reduction policies, while SSP5-RCP8.5 assumes a continued increase in energy consumption and no specific climate change policies. In this study, we used predictions obtained from CMIP6 for calculating basin-level runoff in the above-mentioned scenarios.

To estimate future basin domestic water use, we utilized population projections from Provincial Population Projection data set,³⁵ which predicted China's population from 2010 to 2100 under the SSP1, SSP2, SSP3, SSP4, and SSP5 scenarios, with a spatial resolution of 30 m. Predictions on China's land use (LULC) from ref [36](#) were employed for calculating basin irrigation area and estimating irrigation water use. The data set has a spatial resolution of 1 km, covering 24 scenarios derived from the SSP-RCP framework from 2020 to 2100. For

industrial water use, we relied on insights from reports of ref [37](#), which outlined China's future industrial structure. They have projected phased forecasts of China's GDP growth, with an estimated growth rate of 4.7% before 2030, which is expected to decline to 3.1% thereafter, and the Industrial GDP will account for about 35%. Leveraging multiple future scenarios, our study computed the HWSI for hydropower plants' power generation demand every five years from 2025 to 2060.

To investigate seasonal fluctuations of the HWSI, we calculated the seasonal variations in basin runoff, sectoral water usage, and the water demand for hydropower generation at the plant level. We considered four seasons, including spring (Mar to May), summer (Jun to Aug), autumn (Sept to Nov), and winter (Dec to Feb). The seasonal basin-scale runoff was directly derived from the CMIP6 monthly simulation data. Monthly sectoral water use and variations in hydropower demand under different SSP-RCP scenarios were obtained from a previous literature.³⁸

2.4. Adaptation Strategies Assessment. We tested the effectiveness of four adaptation strategies, including increasing the efficiency of hydropower electricity generation, switching the energy mix to reduce hydropower demand, enhancing water availability through desalination in coastal regions, and reducing water use of agricultural, industrial, and domestic sectors. For each of the strategies, we calculated the reduced number of plants with high HWSI and saved hydropower generation capacity to examine the water scarcity alleviation potentials compared to the baseline level in different future scenarios.

2.4.1. Increases in Total Efficiencies of Hydropower Plants. To reduce water demand for hydropower electricity generation, we consider the first adaptation strategy as enhancing the efficiency of hydropower stations. This entails adjustments to turbine parameters and optimization of operating conditions.⁸ Drawing from prior studies, we classified provincial hydropower generation efficiency into four groups: 0.98–0.95, 0.95–0.92, 0.92–0.82, and 0.82–0.7. We hypothesized that the efficiency of each hydropower plant would improve by one category compared to the baseline condition.²⁵ This assumption thus examines the alleviation of hydropower risk under future scenarios resulting from the enhancement of hydropower generation efficiency.

2.4.2. Local Renewable Energy Substitution. Energy substitution and integration play a vital role in ensuring regional energy stability and mitigating hydropower risks.³⁹ In this study, we focused on regions with well-developed wind and solar energy, defined as provinces with a wind power installed capacity exceeding 10 GW or a solar power installed capacity exceeding 12 GW.⁴⁰ We assumed that 20% of hydropower generation demand for hydropower in these regions can be effectively replaced by wind and solar energy.⁴¹ This assumption is grounded in the expectation that advancements in wind and solar energy technologies will contribute to a viable and sustainable alternative, aligning with the evolving landscape of energy production in the projected scenarios.

2.4.3. Desalination in Coastal Areas. With advances in technology, the scale and volume of seawater desalination projects in China are expanding, especially in coastal regions. The volume of desalination is estimated to reach 2.9 million tons per day by 2025, and the annual usage of seawater for cooling will surpass 1 billion tons, effectively augmenting the

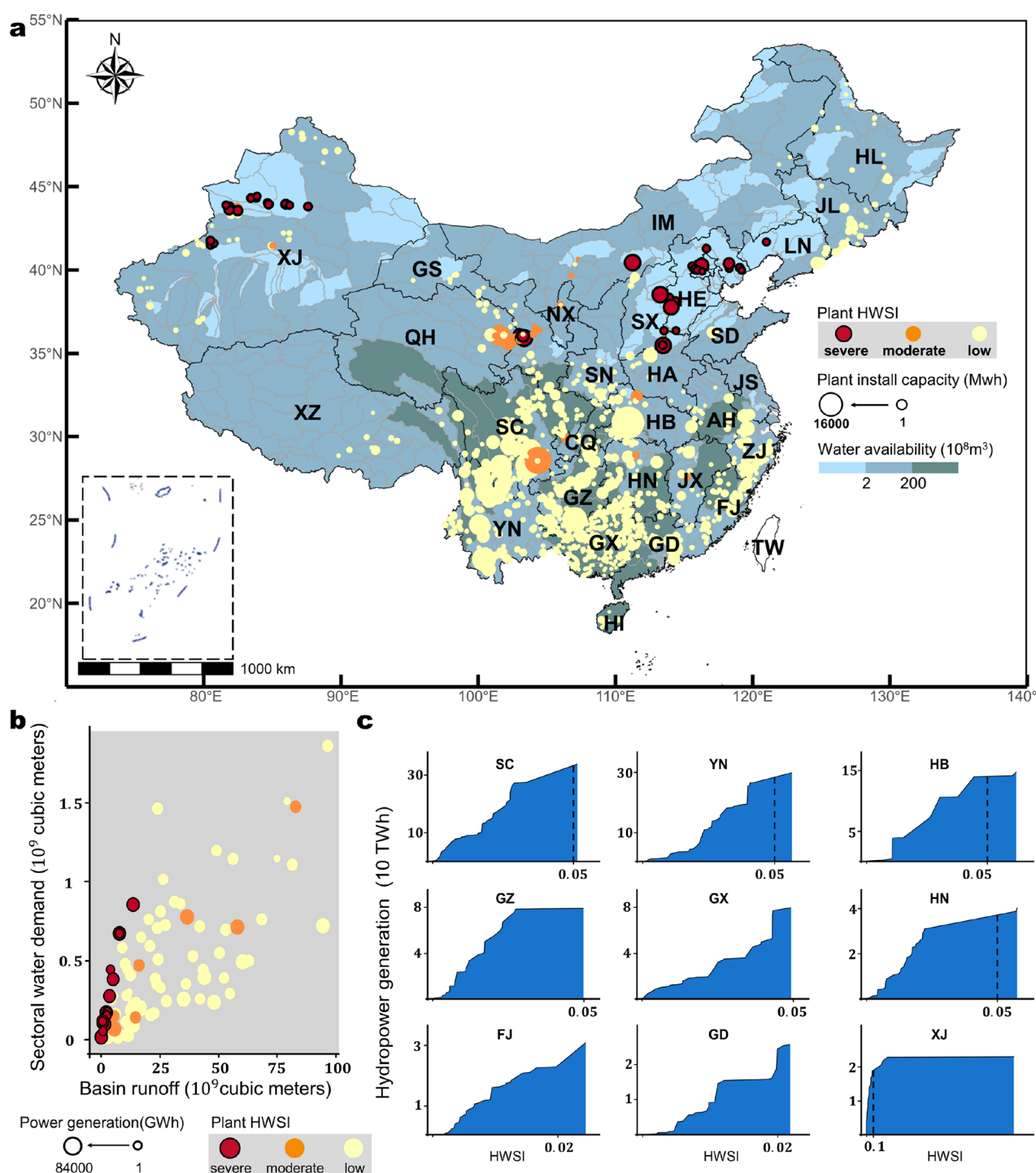


Figure 2. Baseline condition of hydropower plant HWSI in 2018. (a) Maps of hydropower plant HWSI. The colors of the data points reflect HWSI values associated with the power stations, where deeper colors correspond to elevated HWSI values and severe water scarcity risks. Additionally, the size of the points correlates with the installed capacity of the stations, with larger points signifying greater installed capacity. The two-dimensional color map shows the water availability and total sectoral water demand at the level of river basins. (b) The distribution relationship between watershed runoff, sectoral water use, and HWSI of hydropower plants. (c) The cumulative distribution of total provincial hydropower generation at risk. The top nine provinces in China, ranked by installed hydropower generation capacity, are presented here.

water availability and alleviating the pressure on sectoral water usage.⁴² In this study, it is anticipated that future desalination water and seawater cooling water in China can meet 50% of the industrial water demand in coastal areas.⁴³

2.4.4. Sectoral Water Savings and Conservation. To examine how reduced water demand may help relieve hydropower water stress, we assume an increase in sectoral

water-use efficiency, covering agricultural, industrial, and domestic water use. The increased level of water-use efficiency in agriculture, industry, and domestic use sectors was set as 12, 18, and 30%, respectively. The increase ratio pertained to assessments of the potential growth in inefficiencies within sectoral water usage, as documented in previous studies.^{44,45} We employed these adaptation measures at the plant level

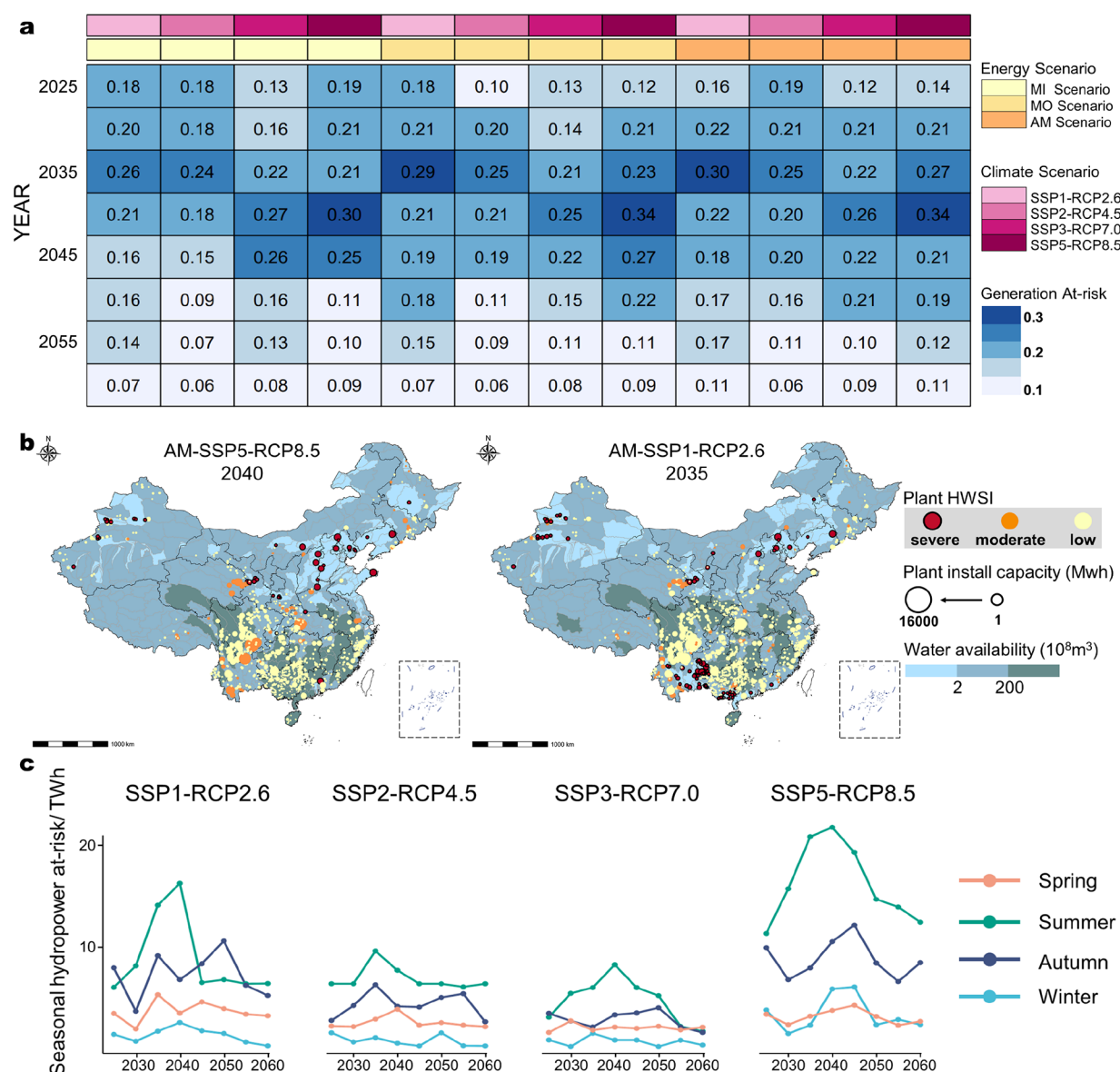


Figure 3. Hydropower water scarcity risks in China under future climate change, energy, and SSP scenarios. (a) The percentage of the total annual hydropower generation capacity exposed to at least moderate water scarcity risks under various scenarios. Combinations of three energy scenarios (MI, MO, and AM) and four climate change (RCP2.6–8.5) and socio-economic scenarios (SSP1–SSP5) are denoted by different colors on the top. Heatmap illustrates the proportion of plants at risk across scenarios and years. (b) Map of the distribution of hydropower plants in the scenario where the largest electricity generation is exposed to at least moderate water scarcity risk and the scenario where the largest number of stations are exposed to at least moderate water scarcity risk. These correspond to the AM energy scenario and SSP5-RCP8.5 climate scenario in 2040 and the SSP1-RCP2.6 climate scenario in 2035. (c) Seasonal hydropower water scarcity risks variation in the AM energy scenario.

according to their feasibility, for example, if the location is near the coast or has adequate wind/solar energy resources. Following this, we reanalyzed the HWSI of hydropower power plants and saved generation capacity to assess the effectiveness of the sectoral water savings measures.

3. RESULTS

3.1. Baseline Water Scarcity Index of Hydropower Plants in China. Figure 2a illustrates the HWSI for each hydropower plant in China during the baseline year of 2018. We find that 47 hydropower stations in China were exposed to severe water scarcity risks as indicated by HWSI values exceeding 0.2, constituting 3% of the country's annual hydropower generation (~36 TWh). Most of these plants were situated in Northern China and Xinjiang Province, areas

confronted with insufficient water supply and high sectoral water use, as highlighted by the light blue shading. These plants exhibit a relatively modest size, featuring an average installed capacity of 250 MW. Power plants with moderate water risk (HWSI values 0.05–0.2) contribute roughly 150 TWh annually, representing about 12% of the nation's total annual hydropower generation. Only 37 plants fall into this category, but they exhibit larger installed capacities, averaging around 1400 MW, with the largest being 7750 MW. These power plants are primarily located in river basins with both abundant water resources and intensive sectoral water use, e.g., in parts of Qinghai (QH), Yunnan (YN), and Hunan (HN) provinces.

Currently, 85% of hydropower plants in China face low water scarcity risk, with HWSI lowering than 0.05. Yet, the

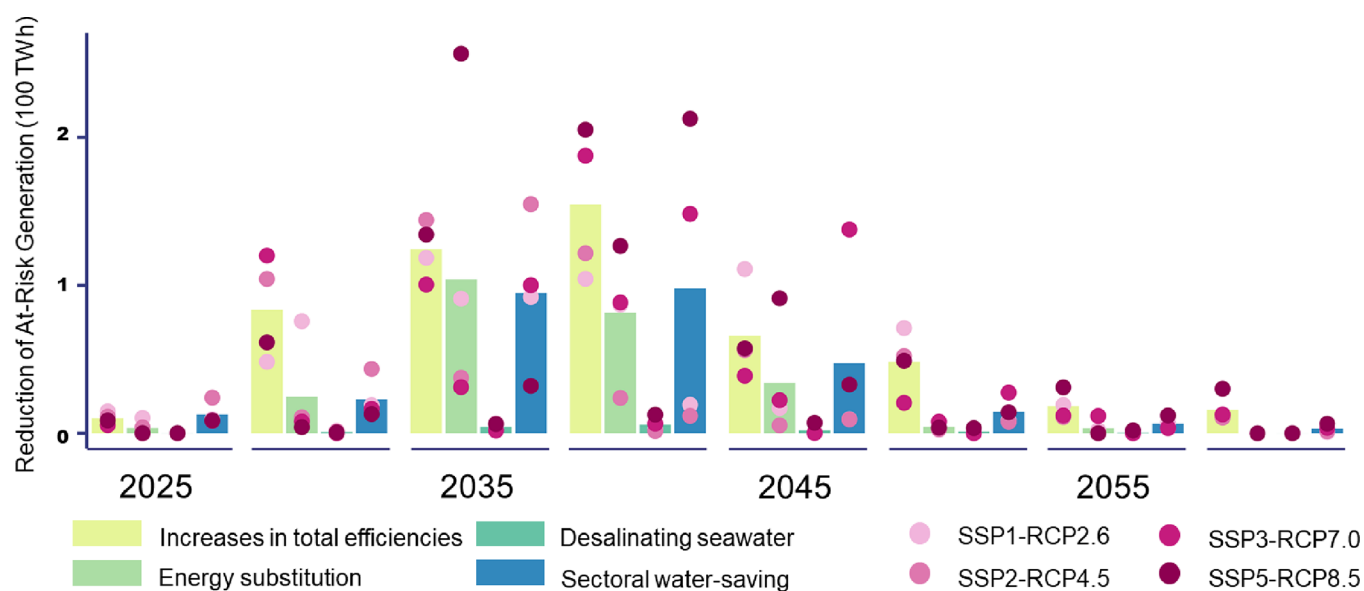


Figure 4. Effectiveness of four adaptation strategies in reducing hydropower water scarcity risks. The bar charts illustrate average reductions in hydropower generation capacity that faces water scarcity risks across four adaptation strategies under the AM energy expansion pathway. Individual dots denote the performance under various climate scenarios.

spatial distribution of these low-risk stations still warrants attention. We find that some clusters with a dense concentration of hydropower plants are spread in regions with high sectoral water demand but limited water availability. These clusters are notably present in specific areas, such as the eastern coast of China spanning Zhejiang (ZJ) and Fujian (FJ) provinces, and the Western Inland Region spanning Sichuan (SC), Chongqing (CQ), and Guizhou (GZ) provinces. Figure 2b depicts the relationship between HWSI, water availability, and sectoral water use in the river basin. It shows that hydropower stations with high HWSI tend to locate in basins with limited runoff or high sectoral water demand, highlighting the role of sectoral water consumption as a significant threat to hydropower generation.

After identifying water scarcity risk hotspots at the power station level, we then calculated the cumulative amount of hydropower generation at risk by province. Figure 2c illustrates the relationships between HWSI values and cumulative hydropower generation for provinces with the highest hydropower installed capacity in China. This provides a clear depiction of the proportion of hydroelectricity generation facing varying degrees of water scarcity across different provinces. In the top three provinces with the largest installed hydropower capacity, including Sichuan (SC), Yunnan (YN), and Hubei (HB), raising the threshold for HWSI values would expose a greater number of hydropower plants to the risk of water scarcity. About 3% (10 TWh), 12% (30 TWh), and 7% (10 TWh) of the existing hydropower generation face HWSI exceeding 0.05 for SC, YN, and HB, respectively. However, if a more stringent water scarcity threshold is implemented (e.g., 0.01 for moderate risk), a high of 70% (230 TWh), 96% (250 TWh), and 90% (130 TWh) of hydropower generation in these provinces would be susceptible to potential losses. Given the potential for more severe drought events in the context of climate change, hydropower plants in these regions may face greater vulnerability than initially expected. We also identify a few provinces, such as Guizhou (GZ), Zhejiang (HN), and Anhui (AH), which exhibit a comparatively higher resilience toward future water risks. Adjusting the HWSI threshold is less

likely to magnify the vulnerability of hydropower generation in these provinces.

3.2. Projections of HWSI for Hydropower Plants in China from 2025 to 2060. We then projected the water scarcity of hydropower plants in future scenarios from 2025 to 2060 with an interval of five years. Basin runoff and sectoral water use were predicted based on four climate change and socio-economic scenarios (see Figure S5). Water demand for hydropower generation was predicted on a plant-by-plant basis, considering three energy expansion scenarios. Full projection results for these parameters can be found in the Supporting Information, Section 2.4.

Figure 3a illustrates the ratio of hydropower generation that is at least exposed to moderate water scarcity risk across scenarios and over years. There are three prominent patterns. First, the time points with the highest hydropower generation risks vary across scenarios. For example, under the SSP1-RCP2.6 scenario, the peak is projected to be in 2035, with a high of 30% of hydropower generation facing at least moderate water scarcity risks (~520 TWh). In the SSP5-RCP8.5 scenario, 34% of hydropower generation (~630 TWh) will face water scarcity risks exceeding moderate levels, peaking by the year 2040. Second, there are widespread declines in the proportion of hydropower plants at risk after the 2050s. This might be because climate scenarios even for the pessimistic ones like RCP8.5 and RCP7.0 forecast increased precipitation in the long term for China especially in southern regions, as illustrated in Figure S7a. Third, the three energy scenarios exhibit small impacts on water scarcity risks. The prevalence of plants with high HWSI has the modest changes across three energy scenarios. In the short run, sectoral water-use competition may be a key constraint factor to cause water scarcity. Figure S7b presents hydropower stations facing moderate-to-high water risks. We note similar patterns, particularly under the SSP1-RCP2.6 scenario, where the highest number of at-risk hydropower stations is anticipated.

Given the complex impacts of climate and socio-economic factors, the distribution of HWSI hotspots for hydropower plants in future scenarios also demonstrates notable spatial

heterogeneity. We selected two extreme scenarios as examples, reflecting the largest at-risk hydropower generation and the highest count of at-risk hydropower stations, as illustrated in Figure 3b,c. We find they exhibit totally different spatial patterns. In the scenario with the largest at-risk hydropower generation (~630 TWh), there are two distinct spatial clusters. In the Northern China Plain, more plants get exposed to severe water scarcity risks mainly due to intensified sectoral water use. In the western–southern region, more hydropower power stations with large installed capacity, including the Three Gorges Dam, the world's largest power station, encounter moderate water scarcity risks stemming from diminished basin runoff. In the scenario with the highest count of at-risk hydropower stations, the hotspot is primarily concentrated in the Southwest and South China regions including GX, GZ, and YN provinces, witnessing an increase of over 70 stations. This is mainly due to the decline in runoff under a pessimistic climate scenario. Although their installed capacity is relatively small, averaging about 300 MW, water scarcity in these plants could potentially exert more direct and significant impacts on local economic activities.

When examining seasonal fluctuations in HWSI, we observe that the summer season experiences the highest risk of hydropower generation scarcity, followed by autumn, spring, and then winter. Despite larger runoff in river basins during summer, hydropower plants may encounter high water scarcity risks due to increased demand for electricity generation and higher water usage across various sectors. Figure 3c displays seasonal HWSI across different climate change scenarios. The most pronounced seasonal fluctuations in HWSI are observed under the SSP5-RCP8.5 scenario. It is projected that hydropower generation will reach peaks of 20 TWh in summer and 12 TWh in autumn during the 2030s–2040s. Additionally, there is a notable increase in summer hydropower generation under the SSP1-RCP2.6 scenario, possibly influenced by assumptions of rapid hydropower expansion in the near term. However, the risk of water scarcity for hydropower in spring and winter remains consistent across different scenarios, likely due to their comparatively lower power generation demands. The spatial patterns of seasonal HWSI are in line with our findings on an annual basis (Figure S8), and we have elaborated more in the Supporting Information, Section 2.4.

3.3. Effectiveness Analysis of Adaptation Strategies.

Finally, we tested the effectiveness of four adaptation strategies that may help relieve future water scarcity risks of hydropower systems. Figure 4 presents the performance of each strategy in mitigating hydropower generation capacity that faces water scarcity risks across various scenarios and over time.

We find enhancing hydropower efficiency is efficient to mitigate water scarcity risks for hydropower plants, especially in the short run. Enhancements in generation efficiency have the potential to alleviate water scarcity risks by up to ~200 TWh, constituting 11% of China's annual hydropower generation. It is the most reliable strategy to ensure the stability of hydropower generation activities over years. Then, the feasibility of desalinating seawater is restricted to coastal regions. A larger number of hydropower plants are located inland in China, thereby constraining its efficacy in mitigating the water scarcity risks of hydropower generation. This approach, at its most optimistic, only allows for approximately 1% of hydropower generation to relieve water scarcity risks. Hence, other approaches to increase physical water availability should be considered, such as upstream water conservation.⁴⁶

The substitution of renewable energy sources is another robust solution. This strategy consistently demonstrates effectiveness throughout the simulated time frame, saving up to 16% of China's annual hydropower generation, which amounts to ~260 TWh, from water scarcity. This highlights the importance of substantial future development of variable renewable energy (VRE) to ensure energy security and stability.^{18,47} Sectoral water saving and conservation prove to be another important measurement, capable of reducing water scarcity risks for hydropower capacity by a maximum of ~210 TWh when implemented in 2040 under the SSP5-RCP8.5 scenario. It accounts for over 12% of China's annual hydropower generation. This adaptation measure is particularly effective in the SSP1-RCP2.6 and SSP5-RCP8.5 scenarios, where runoff is relatively low, making water conservation important in mitigating water scarcity risks. This also underscores the pivotal role of sustainable water management and conservation efforts in safeguarding hydropower generation security.

4. DISCUSSION

In this study, we formulated a Hydropower Water Scarcity Index (HWSI) specifically for hydropower plants and evaluated the hydropower generation in China that is susceptible to losses from water scarcity. The analysis covered the baseline year of 2018 and extended to future scenarios spanning from 2025 to 2060 and considered seasonal variation of HWSI for each year. We identified hydropower plants that are vulnerable to current and future water scarcity, mapped their fine-scale spatial distribution, and examined feasibility of various types of adaptive strategies.

Our study makes the following two main innovations: methodologically, this study develops a plant-level Hydropower Water Scarcity Index (HWSI) with strong generalization capabilities to assess the risk of power generation reduction caused by water scarcity for hydropower stations worldwide. Unlike water footprint studies that perceive hydropower production as a process of water consumption, potentially worsening local water scarcity, this approach, for the first time, addresses the inverse process. It examines how complex factors of water scarcity constraints may affect hydropower generation, thereby enriching research on the water-energy nexus topics. Next, from a mechanistic perspective, this study untangles the contributions of climate change, sectoral competition, and energy expansion in relation to the water scarcity risks confronting hydropower plants within the Chinese context. Integrating both the technical specifications at the plant level and the unique conditions of the river basin enables the identification of spatial variations and forecasts temporal shifts in primary contributors of water scarcity. This underscores the importance of implementing localized adaptation strategies and devising low-carbon energy expansion plans to safeguard water-energy security.

Our findings align with various global assessments of power system vulnerability, yet also offer novel insights. For instance, we identified hydropower generation risks in China that are distributed in regions similar to previous global-scale predictions under the same climate scenarios. By 2050, substantial hydropower production risks are expected in Southwestern and Southern China, with nearly a 20% decline.¹⁶ Similarly, findings reported a decrease in usable power plant capacity in the same regions of China during the 2050s.⁸ Our study confirms these findings but also reveals

some different patterns. For example, we highlight that the increase in hydropower water risk is primarily influenced by sectoral water competition and global climate change, while the impact of hydropower expansion on water risk is comparatively less pronounced. Notably, in most river basins, agricultural sector emerges as the primary competitor for water resources in hydropower generation. However, in Northern China and along the southeastern coast, the industrial sector is the predominant competitor for water resources in hydropower generation in the future scenario. We also find due to heightened competition of sectoral water use in the short term, hydropower water scarcity risks might reach their peak between the 2030s and 2040s. However, conditions are expected to improve after the 2050s, due to a general increasing trend of runoff. It highlights the need to take immediate action in the near future.

To achieve the goal of carbon neutrality, China planned to expand the installed capacity of hydropower to 700 GW by 2060. Our findings offer practical implications for mitigating water scarcity risks of hydropower plants. Prior studies have demonstrated the efficacy of engineering approaches to enhance hydropower generation efficiency, such as adopting water-saving turbines, enhancing equipment maintenance, and optimizing generator operations. Findings suggest that these strategies could increase electricity yields by 5–20% and achieve water savings of 10–15%.^{18,48} Our study further demonstrates that improving water-use efficiency has the potential to effectively alleviate water scarcity risks for 11%, particularly in the short term.

Additionally, we underscore the importance of river basin management solutions, such as sectoral water savings and conservation measures. These approaches may surpass the potential of solely engineering-based solutions in certain river basins. Local policymakers may consider enforcing regulations on the total volume of sectoral water use or employing economic policy instruments to incentivize water-saving practices. China is implementing a strategic national policy known as the “Water Network Project”, aimed at achieving the balanced allocation and optimal utilization of water resources across regions. Our study provides practical insights for this project by guiding more flexible water allocation and management strategies across river basins to balance the water-energy nexus and enhance downstream water-use efficiency.

From the power generation side, joint scheduling and dispatching of diverse energy resources is crucial to ensure sustainable energy generation. The substitution of renewable energy sources such as wind and solar energy, as proved highly effective in our study, can contribute more to alleviating hydropower risks. Promoting pumped-storage hydropower stations also helps reduce hydropower wastage and enhance the capacity for clean energy absorption and storage in achieving energy transition. In addition to developing a water–wind–solar energy system, studies confirmed the potential of floating photovoltaic (FPV) systems to balance electricity generation from reservoirs during rainy and dry seasons. Leveraging the complementary nature of solar and hydropower generation, this setup efficiently meets the growing demand for clean electricity and enhances energy security.⁴⁹ Then, building a nationwide electricity market is also a crucial means for more efficiently allocating electricity and ensuring a stable supply. By participating in the nationwide electricity market, the south-west provinces such as Yunnan (YN) can optimize resource

allocation by receiving electricity from other regions when facing drought and integrating renewable energy into the power grid during periods of surplus supply.

Finally, optimizing local industrial structure and reducing power and water demand are also important pathways to relieve water scarcity risk from the demand side. Taking Yunnan province as an example again, to boost local electricity consumption and absorb hydropower, local governments introduced policies to attract industrial enterprises, especially for aluminum smelting industry since 2016. Although it resolves curtailment of hydropower, in recent years, the emergence of unusual weather conditions poses significant challenges to ensuring local power supply nowadays. Thus, it is crucial to proceed with energy-saving and water-saving measures in local industries to enhance the resilience of facing the risk of water scarcity-related losses in hydropower generation.

Hydropower plays a crucial role in balancing intermittent renewables such as wind and solar. However, when water is scarce, hydropower plants cannot operate as flexibly, thereby limiting their effectiveness in smoothing out fluctuations in power supply from intermittent sources. This challenge is particularly prominent in China, where many renewable energy hubs for solar and wind are located in the northern and western regions, already facing constraints in water resources. This further diminishes their ability to effectively balance energy generation. Therefore, it is imperative for future studies to delve deeper into the impacts of hydropower water scarcity on the balancing and integration of intermittent renewables, as this understanding is essential for ensuring the stability and secure deep decarbonization of the power system.

We acknowledge here a few uncertainties and limitations in the current study. First, we assumed a static operational condition of power generation. In practice, the efficiency of hydropower plants may decrease, leading to varied water demand.⁵⁰ Also, hydropower generation requires certain reservoir storage, and the actual water demand should be greater than simply deriving from runoffs.^{51,52} Thus, the real water scarcity risk for hydropower generation in China's future may be more severe than our conservative assessment in this study. Second, we did not consider interbasin water transfer projects in China. For instance, the South-to-North Water Diversion Project in China increases available water resources in the Northern China Plain, which might reduce water scarcity risks for hydropower. Third, flexible reservoir management could help release stored water when natural water sources are scarce and adjust to optimize energy production.⁵³ This study fails to simulate these complex reservoir management processes and does not test their effectiveness in mitigating water scarcity risks.⁵⁴ Finally, we only simulated annual mean trends in future climate change scenarios but did not consider extreme events such as droughts or monthly fluctuations in streamflow. Some hydropower stations may exhibit greater vulnerability to short-term shocks due to their inability to make timely adjustments.

■ ASSOCIATED CONTENT

Data Availability Statement

Data used in this study are all from publicly accessible resources and have been cited or mentioned in the main texts and the method section. The data that support the findings of this study are available upon reasonable request from the authors.

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.est.4c00671>.

(SI Text) Assumptions used plant-level hydropower increase calculations, description of water demand and consumption for hydropower, annual runoff variability and sectoral water consumption dynamics, variation of high-HWSI plant under multiscenarios, seasonal at-risk hydropower generation and adaptation strategy analysis; (SI Figure/Table) distribution of hydropower plants in China, scatter plot of observed values versus simulated values of provincial runoff, maps of the most dominated water-use sectors by basin, overview of data involved, and abbreviations by provinces (PDF)

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Notes

The authors declare no competing financial interest. Code used in this study will be made available on reasonable request.

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