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Water security implications of coal-fired power plants financed through China's Belt and Road Initiative

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ABSTRACT

As the world's largest proposed infrastructure program, China's Belt and Road Initiative will have significant implications for water security, sustainability, and the future of energy generation in Asia. Pakistan, a keystone of the Belt and Road Initiative, presents an ideal case for assessing the impacts of the Initiative's energy financing. We estimate the future water demands of seven new Chinese-financed, coal-fired power plants in Pakistan with a total capacity of 6600 MW. While these facilities may help address Pakistan's energy shortages, our results indicate that by 2055, climate change-induced water stress in Pakistan will increase by 36–92% compared to current levels, and the power plants' new water demands will amount to ~79.68 million m^3. Our findings highlight the need for China and the Belt and Road Initiative's destination countries to integrate resilience and sustainability efforts into energy infrastructure planning. Policy recommendations are offered to permit both sustainable development and responsible water resource management.

1. Introduction

Chinese financing of energy infrastructure through the Belt and Road Initiative (BRI) will significantly influence the energy mix for much of Asia in the coming century. Initially proposed in 2013 and currently in its early stages, BRI seeks to establish both a land-based "Silk Road Economic Belt" and a "Maritime Silk Road," prioritizing economic development and international partnership (Swaine, 2015) while promoting energy cooperation (Duan et al., 2018). Siting and planning new power plants will create large fixed investments, having serious implications for both global carbon emissions and the feasibility of sustainable development in the approximately 70 destination countries which are expected to participate; these countries account for 65% of the world's population.

BRI offers tremendous opportunities for economic growth and poverty elimination, the latter of which is prioritized by the Sustainable Development Goals (SDGs) put forth by the United Nations (Cohen, 2006; Huang, 2016; United Nations, 2018). However, this economic benefit may come at the expense of other SDGs. For instance, BRI projects involving the establishment of new energy facilities, particularly coal-fired power plants, should be evaluated on the basis of their sustainability and climate resilience implications. Many of these coal-fired plants will be constructed in arid and semi-arid regions of southern Asia and Africa, including countries like Pakistan, which are considered water-insecure (Mekonnen and Hoekstra, 2016).

In this study, we focus on Pakistan for analytical tractability. However, we note that there are seven other countries that, like Pakistan, have committed BRI investments in coal-fired power exceeding US $1 billion, as well as 22 other countries with proposed capacity installation of over 500 MW (Shearer et al., 2019). Coal-fired

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power plants simultaneously increase greenhouse gas emissions and use large quantities of water, mainly for cooling purposes (Feeley et al., 2008; Sims et al., 2003). As such, construction of these energy facilities may contradict at least three SDGs which seek to (A) reduce water scarcity, (B) increase the incorporation of renewable energy sources, and (C) otherwise address climate change (United Nations, 2018).

The potentially adverse impacts of BRI-related energy infrastructure have a global reach. Chinese financing of energy facilities has influenced infrastructure investment decisions and shaped the global power mix even before the initiation of BRI (Gallagher, 2017). Chinese financing provides both competition and alternative sources of capital, influencing the actions of other multilateral lenders in the power sector (Hannam, 2016; Hannam et al., 2015). From a global perspective, China financed energy projects in 121 countries from 2000 to 2013, with coal-fired power plants making up nearly a third of this investment (Gallagher, 2017). Under BRI, this investment increased and involved China in 240 coal-fired power projects across 25 countries by the end of 2016 (Ren et al., 2017). Considering their potential to influence the future of energy infrastructure around the world, it is critical to understand how these coal-fired power plants will impact sustainability and water security.

Here, using scenario-based simulations, we provide a novel framework for quantitative assessment of the water stress related to coal-fired power plants in BRI destination countries. While focusing on Pakistan as a case study, our framework can be broadly applied to other BRI countries, providing insights for future sustainable planning in the energy sector. Specifically, we ask: (1) will BRI-affiliated coal-fired power plants in Pakistan require substantial quantities of water for cooling purposes? If so, (2) will this cooling water withdrawal and consumption exacerbate existing water scarcity in Pakistan, especially given future climate changes?

To address these questions, we use a large-scale hydrological and water resources model to estimate past, present, and future projections of water stress in Pakistan. Modeling is performed with a multi-model ensemble framework to account for inherent model uncertainties. We then calculate the cooling water demand of seven Chinese-financed coal-fired power plants in Pakistan. Our results show that the installation of new facilities in Pakistan will increase local water scarcity due to the combination of climate change-induced water stress and heightened water demands for power generation. This research provides the first precise, quantitative evaluation of BRI-based investment in Pakistan's power sector. Policy actions are suggested that permit economic development, within the framework of the BRI, while ensuring water and other resource sustainability.

1.1. The coal-water nexus in Pakistan

Pakistan is selected as a case study because energy financing through the China-Pakistan Economic Corridor (CPEC) is amongst the most prominent and widespread of BRI projects. Chronic power shortages are a severe issue in Pakistan, lowering annual GDP by 7% (Feng and Saha, 2018). These shortages could be partially alleviated by CPEC projects which designate $62 billion for developing infrastructure in Pakistan, two-thirds of which will be directed towards the energy sector. At the same time, Pakistan faces many challenges to sustainable development—common to many developing nations—and has historically treaded a fine line between water use and socioeconomic development (Satoh et al., 2017). The nation's water challenges are primarily driven by overexploitation of groundwater, saltwater intrusion, low-efficiency irrigation, and poor infrastructure for water treatment and storage (Kahlown and Majeed, 2003). In Pakistan, 95% of the water supply is consumed by agriculture, which, as a sector, involves around 60% of the population and generates 80% of national exports annually (Kundi, 2017). Domestic and industrial water uses (i.e., the remaining ~5%) continue to compete with agricultural demands (Kahlown and Majeed, 2003). All told, Pakistan has the fourth-highest rate of water consumption in the world (Huang et al., 2017).

As such, water is a commodity whose use in Pakistan and other nations must be carefully managed. Even so, Chinese-financed energy infrastructure development under BRI includes the establishment of water-intensive coal-fired power plants. In this study, we examine the water demands introduced by BRI's seven continental coal-fired power plants in Pakistan (lettered A–G; see Table A1 for details) having a total generating capacity of 6600 MW and estimated cost of at least US $11 billion; all seven plants require freshwater for cooling purposes. The seven plants of interest are selected because they are either currently operational or expected to be operational by the year 2022. Importantly, this means that their cooling systems are fixed and will not be impacted, at least in the near future, by advances in cooling technology. The plants are located near densely populated load centers including Karachi, which neighbors two of CPEC's Special Economic Zones, and the Sindh and Punjab provinces. The power plants will therefore provide vital electricity for domestic and industrial use. However, the plant locations also coincide with regions of existing water stress. Considering the lifetime of power plants (~40 years), these facilities will likely operate until 2055 or beyond, during which time they will influence Pakistan's water security, already worsening due to climate and socioeconomic changes.

Water-related concerns associated with coal-fired power plants stem from the fact that water is used in multiple steps of the energy generation process. A small amount of water is heated to produce steam needed to rotate a turbine, thereby generating electricity, and some may also be used to treat environmental emissions (Hasibeck et al., 2010). However, a much larger quantity of water is required to cool the steam back to liquid water, allowing the steam source to be recycled. The cooling water makes up the bulk of the water supply required in coal-fired power generation. Specifically, cooling water withdrawals per MWh of generated electricity range from 34–182 m^3 for once-through cooling systems and 0.02–9.8 m^3 for recirculating cooling towers (Macknick et al., 2012). Variations in cooling water demand depend on the thermal efficiency of the power plant, temperature of the intake water, design of the cooling system, and meteorological conditions (Bartos and Chester, 2015). In water-insecure areas, the demands of coal-fired power stations can compete with alternative demands made by agriculture, health, and other socioeconomic applications requiring adequate water access (Luo et al., 2018).

In this study, we use the ratio of water withdrawal to availability as a representation of the Water Stress Index (WSI, see Methods for details) to assess the past, present, and projected water stress conditions in Pakistan. WSI is obtained based on the multi-model and multi-scenario assessments of the Water Futures and Solutions (WFaS) Initiative (Wada et al., 2016) with a focus on Asia (Satoh et al., 2017) from 1971 to 2055 at 50-km spatial resolution. As water stress is jointly influenced by climate change (Schewe et al., 2014) and socioeconomic development (Arnell, 2004; Gosling and Arnell, 2016; Vörösmarty et al., 2000), the conventional Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs, O'Neill et al., 2014) should be combined to drive the global hydrological models for more accurate and comprehensive assessment. Therefore, WFaS extends the original SSP scenario beyond its typical focus on key climate policy drivers (O'Neill et al., 2014) by emphasizing water use and availability across sectors based on country-level hydro-economic classification (Hasibeck et al., 2010; Satoh et al., 2017).

According to this classification, Pakistan is a region characterized by both water stress and low coping capacity, which may introduce a series of challenges for sustainable development. Following Wada et al. (2016) and Satoh et al. (2017), we use a combination of SSP2 (i.e., middle-of-the-road scenario indicating a medium level of adaptation and mitigation) and RCP6.0 (i.e., medium emissions scenario) to approximate middle-of-the-road projections for future climate and socioeconomic changes. Because hydrological responses to meteorological forcings are inherently uncertain, we use bias-corrected projections from five different Global Climate Models (GCMs; see model details in Table A2) to add robustness to our findings. We then calculate the cooling water demand of seven Chinese-financed coal-fired power plants in Pakistan using a heat and water balance model (Bartos and Chester, 2015) driven by projected meteorological data, water temperature, and mean historical capacity factor (see Methods for details).

2. Materials and methods

2.1. Calculation of Water Stress Index

In this study, the Water Stress Index (WSI) is defined as the ratio of water withdrawal to total available surface water, which is often employed in the literature to characterize local water stress situations (Alcamo et al., 2003; Satoh et al., 2017; Zhang et al., 2016). We calculate WSI based on the simulated water withdrawal and availability from three previously validated global hydrological models (GHMs), including H08 (Hanasaki et al., 2008), PCR-GLOBWB (He et al., 2017; Sutanudjaja et al., 2017; van Beek et al., 2011; Wada et al., 2014), and WaterGAP (Flörke et al., 2013; Müller Schmied et al., 2014). The GHMs simulate the historical water withdrawal and availability using historical weather data and water withdrawal data (Satoh et al., 2017). The GHMs simulate the future water withdrawal and availability using scenarios developed with water planners and stakeholders, as well as the downscaled Global Climate Model (GCM) projections from the Inter-Sectoral Impact Model Intercomparison Project fast track, which is based on GCMs from the Coupled Model Intercomparison Project Phase 5 (Hempel et al., 2013; Warszawski et al., 2014; Satoh et al., 2017). The "future" simulations of each GHM span the combination of three SSP scenarios and five bias-corrected GCM projections under RCP4.5 and RCP6.0. We calculate the ensemble average of these three GHMs for each individual GCM. Here, we focus on the SSP2/RCP6.0 scenario, but results from the other two scenarios (i.e., SSP1/RCP4.5 and SSP3/RCP6.0) are also presented in the Appendix. These two scenarios represent the lower and upper ranges of possible changes in climate and socio-economic development.

2.2. Water temperature estimation

To generate water temperature estimates, we use a novel coupled hydrological-energy model. Hydrological fluxes of surface runoff, overland flow, and groundwater discharge are estimated using the global hydrological model PCR-GLOBWB 2 (Sutanudjaja et al., 2017). These fluxes are then used by a dynamical 1-D energy routing model (Wanders et al., 2019) to produce estimates of water temperature. Both models simulate the hydrological cycle at a 10-km spatial resolution and daily temporal resolution. The water temperature model assumes fully mixed rectangular channels and is able to simulate lakes and reservoirs. Reservoir operations mimic an operations schedule that would be optimal for hydropower generation. The model allows for the simulation of ice formation and break-up, both of which impact water flow in streams and rivers. Point source advection from industrial cooling water is currently not included in this model. The model has been proven to provide accurate water temperature simulations and can be used with confidence to generate water temperature estimates (e.g., van Vliet et al., 2016).

2.3. Calculation of cooling water demand

Based on existing analyses of cooling technologies in southern Asia, including newspaper coverage of Pakistani plants and detailed analyses of India's cooling technologies (Luo et al., 2018), we note that use of dry cooling technology is extremely rare. Thus, we assume the coal-fired power plants (Table A1) will use cooling towers and estimate the water withdrawal (WI_{rc}, m^3 MWh^{-1}) and consumption (CI_{rc}, m^3 MWh^{-1}) factors using a previously reported heat-and-water-balance model (Bartos and Chester, 2015), models which we re-arrange to produce Equations (1) and (2). With regard to the ambient environmental conditions in Equation (1), the ambient wet-bulb temperature (T_{wb}), humidity ratio of air entering the tower (ω_{in}), and enthalpy of air entering the tower ($h_{a,in}$) are calculated from the downscaled air temperature, relative humidity, and surface pressure from the five GCMs (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, NorESM1-M) using standard psychrometric relationships (Stull, 2011). The temperature of the intake water (T_{in}) comes from the water temperature simulated by PCR-GLOBWB 2 (Wanders et al., 2019). The humidity ratio of air exiting the tower (ω_{out}) is assumed to equal the saturation humidity ratio at ambient atmospheric pressure and temperature. The enthalpy of the air exiting the tower (h_{out}) is calculated from ω_{out} and ambient temperature using standard psychrometric relationships (Stull, 2011). The density of water (ρ_w) is 1000 kg m^{-3} and the heat capacity of water (C_p) is 4.184 J g^{-1} °C^{-1}.

$$WI_{rc} = \frac{1-\eta_{net}-k_{os}}{\eta_{net}} \cdot \frac{\omega_{out}-\omega_{in}}{\rho_w\left[(h_{a,out}-h_{a,in})\left(1-\frac{1}{n_{cc}}\right)+\left(\frac{T_{wb}+T_{app}}{n_{cc}}-T_w\right)C_p(\omega_{out}-\omega_{in})\right]} \quad (1)$$

$$CI_{rc} = \left(1-\frac{1}{n_{cc}}\right)\times WI_{rc} \quad (2)$$

With regard to the cooling tower parameters in Equation (1), we set the cycles of concentration (n_{cc}) to 5, which is the upper limit prescribed in the electricity industry standard of China ("Electricity industry standard of the People's Republic of China - guide for water saving of thermal power plant. State Economic and Trade Commission," 2002). Since the water withdrawal factor of cooling towers decreases with the cycles of concentration, using the upper limit means that the estimated water withdrawal factor will be a conservative estimation. We assume that the fraction of heat loss through flue gas and other dissipative pathways (k_{os}) is 12%, following the original study (Bartos and Chester, 2015). We set the approach of the cooling tower to 6 °C; the normal range of the approach parameter is 4–8 °C (Bartos and Chester, 2015), and preliminary analysis showed that the water withdrawal factor is not sensitive to the approach parameter. We estimate the net thermal efficiency (η_{net}) of the seven power plants from their installed capacities (Table A1) by fitting linear and lognormal relationships between the installed capacity and thermal efficiencies of supercritical and subcritical coal-fired power plants in a previous dataset (Raptis et al., 2016; Raptis and Pfister, 2016) (Fig. A1).

Using the estimated water withdrawal and consumption factors from Equations (1) and (2), we calculate the annual water withdrawal (W, m^3 year^{-1}) and consumption (CS, m^3 year^{-1}) of the power plants using Equations (3) and (4), respectively. For capacity factors (cf, unitless between 0 and 1), we use the average capacity factor of thermoelectric power plants in Pakistan from 1970–2013 (IAEA, 2017), similar to the approach taken in (Holbert and Haverkamp (2009)). The numbers in Equations (3) and (4) are for unit conversion.

$$W = WI_{rc}\cdot C\cdot cf\cdot 24\cdot 365 \quad (3)$$

$$CS = CI_{rc}\cdot C\cdot cf\cdot 24\cdot 365 \quad (4)$$

3. Results

3.1. Current water stress situation

To determine the water demands imposed by power plants A–G relative to Pakistan's freshwater supply, it is first necessary to understand the nation's current and future water availability, the latter of which may be impacted by climate stresses. The 10-year averaged WSI from 2006 to 2015, shown in Fig. 1, serves as a measure of the current water availability and indicates that the central and southern regions of

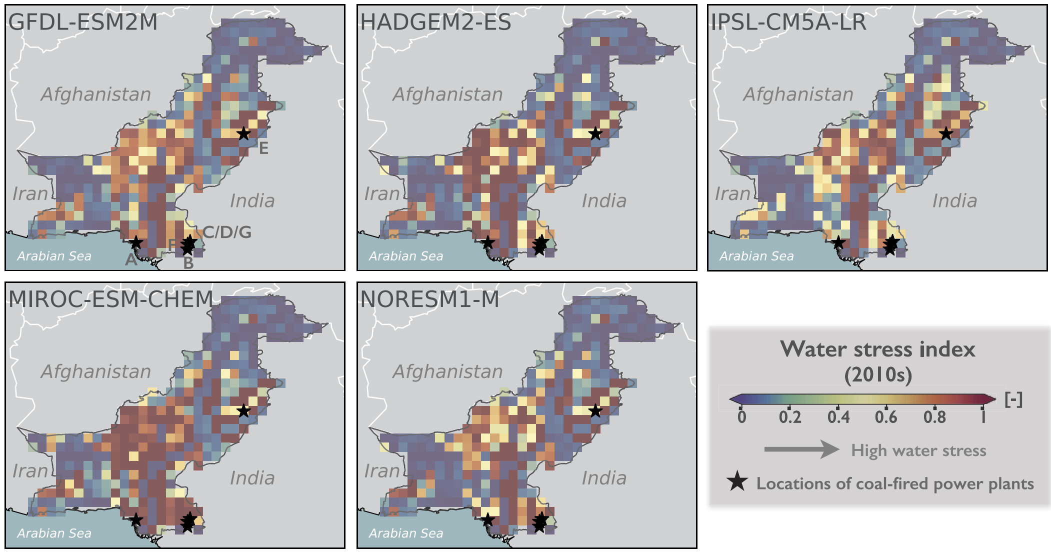

Fig. 1. Spatial distribution of the WSI averaged from 2006 to 2015, based on forcings from five GCMs under SSP2/RCP6.0. Letters A–G in the upper left panel correspond to plant IDs (see details in Table A1 and Fig. A2), where plants were selected to include existing, under construction, and planned facilities financed by China.

Pakistan are now experiencing severe water stress. In contrast, northern Pakistan has generally low WSI values (i.e., less than 0.2), indicating that this region is not presently under water stress (see the definition of "water stress" in Satoh et al., 2017). This spatial pattern is generally consistent and robust across all five climate models, with slight differences illuminated in parts of central Pakistan.

Based on these estimates, all seven coal-fired power plants under study, identified by stars in Fig. 1, are located in areas currently experiencing severe water stress. Meeting the cooling water demands of these power stations will therefore already be challenging, even before considering future climate projections. However, it should be noted that at least two of the seven power plants utilize supercritical technology (the technology employed in the newest plant has yet to be reported, and here it is assumed to be supercritical), resulting in slightly higher energy efficiencies. These supercritical plants will require less water to generate electricity (per MW) compared to non-supercritical power stations, though the most important driver of cooling water demand magnitude is generation capacity. The three supercritical plants have efficiencies between 42 and 45%, while the remaining four sub-critical plants exhibit efficiencies around 38%. Additional details can be found in Table A1 and Fig. A1.

3.2. Trends and relative changes in water stress by the 2050s

Pakistan's future water availability under the SSP2/RCP6.0 scenario is represented by the WSI trend (Figs. 2 and 3) and relative changes (Fig. 4) from 2046–2055, which can then be compared to both recent years (2006–2015) and a historical period (1971–2004). Considering the historical period, four of the five models indicate that no statistically significant WSI trend exists (i.e., 95% significance level) when averaged across the entire country, which is mainly due to natural variability. Only HADGEM2-ES shows a statistically decreasing trend, indicating a wetting of the region in the historic period. However, this statistically significant trend does not hold for future projections made by the same model. In contrast, the four other models project statistically significant increases in the WSI trend; these increases have relatively small magnitudes ranging from 0.001 to 0.002/year. For the whole study period and across all models, Pakistan's average WSI is greater than 0.2, reinforcing our previous finding that Pakistan is and will remain under water stress over the long-term.

In Fig. 3, the linear trend in WSI from 2006 to 2055 illustrates large spatial variability across all five models. For instance, three of the five models (i.e., GFDL-ESM2M, IPSL-CM5A-LR, NORESM1-M) exhibit a statistically significant increasing trend in central Pakistan. The largest trends in these three models exist for the region near the power plants in southeastern Pakistan (i.e., B, C, D, F, G). In contrast with the other models, HADGEM2-ES exhibits decreasing water stress spreading in parts of central Pakistan, but these trends are not statistically significant. Regions that are not currently water stressed will likely experience stress at the hands of future climate changes and socioeconomic development; this is demonstrated by consistent increasing trends produced by all models, as shown in northern Pakistan. Therefore, we must still account for long-term water stress.

The relative water stress changes in the 2050s compared to the current situation (i.e., 2006–2015) are displayed in Fig. 4 (i.e., for the entirety of Pakistan) and Table A3 (i.e., at project level). All five models consistently project increasing water stress ranging from 36 to 92% over the entirety of Pakistan, with regional hotspots in the northern and southwestern portions of the country. However, HADGEM2-ES and IPSL-CM5A-LR project slightly decreasing water stresses over central and eastern parts of Pakistan, respectively. Like the findings of the linear trend estimation, no significant changes are anticipated for power plant A. However, water stress will intensify for the regions containing power plants B, C, D, F, and G in the 2050s. In general, we conclude that the regions in which the power plants are situated or proposed will face increasing water stress.

We repeated the above analysis for the SSP1/RCP4.5 and SSP3/RCP6.0 scenarios, representing the lower and upper bounds of possible climate and socioeconomic development changes. All three scenarios demonstrate similar trends in projected future WSI (Fig. 2, Fig. A3, A4), albeit at slightly different confidence levels (i.e., generally higher *p*-values were achieved for SSP1/RCP4.5 and lower *p*-values were calculated for SSP3/RCP6.0 compared to SSP2/RCP6.0). These results are also reflected in the spatial maps of linear WSI trends (Fig. 3, Fig. A5, A6) and relative WSI changes (Fig. 4, Fig. A7, A8). For instance, compared to SSP2/RCP6.0 (Fig. 3), SSP1/RCP4.5 has a smaller magnitude of WSI trends and a reduced number of pixels with statistically significant trends (Fig. A5). As expected, with more resource-efficient economies (i.e., SSP1) and reduced carbon emissions (i.e., RCP4.5), water stress can be alleviated in the 2050s (Fig. A7 vs. Fig. 4). Interestingly, the spatial distribution of linear WSI trends and relative WSI changes are generally similar between SSP2/RCP6.0 and SSP3/RCP6.0 (Fig. 3 vs. Fig. A6; Fig. 4 vs. Fig. A8), indicating that changes in water

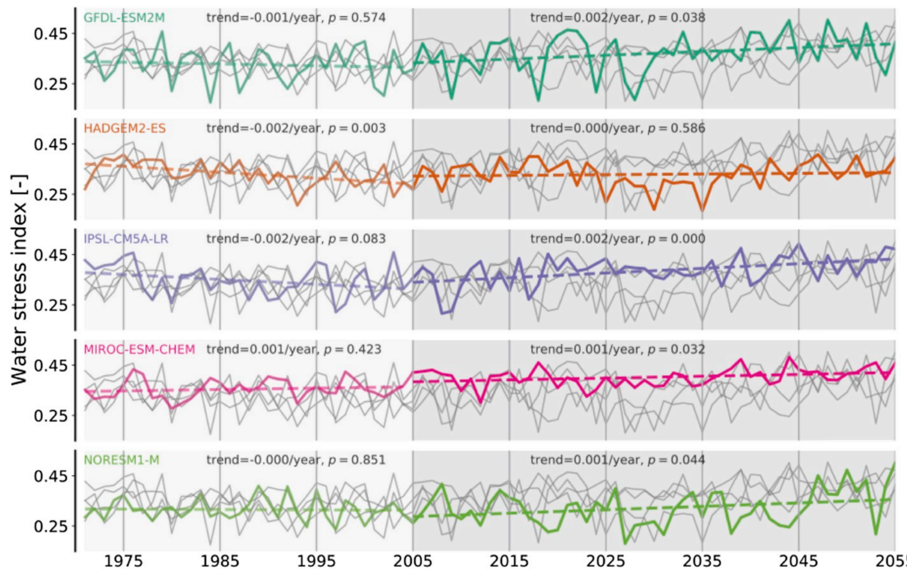

Fig. 2. Time series (solid lines) and linear trends (dashed lines) of WSI averaged over all of Pakistan in the historical (1971–2004) and future (2005–2055) periods projected by five GCMs under SSP2/RCP6.0.

stress in Pakistan might be dominated by climate (i.e., RCP) rather than socioeconomics (i.e., SSP).

At the project level (Table A3), we found that only under the SSP1/RCP4.5 scenario are future changes in local water stress conditions not significant (i.e., less than 15%). With higher emissions and socioeconomic development (i.e., SSP2/RCP6.0 and SSP3/RCP6.0), current local water stress conditions are expected to increase by more than 75% in the future, especially for plants C, D, F, and G, which are located in regions with limited water availability.

3.3. Cooling water withdrawal and consumption

The seven BRI-affiliated coal-fired power plants examined here could theoretically intensify the current water stress situation given the fact that water is needed to meet plant cooling demands. To test this hypothesis, the total cooling water withdrawal (CWW) and consumption (CWC) were calculated from 1971 to 2055 based on the heat-and-water-balance model (Bartos and Chester, 2015) (Fig. 5, Fig. A9, A10). We extend the study period back to 1971, which is counterfactual in reality, in order to examine the relative influence of future climate changes and socioeconomic development when compared to historical conditions.

Consistently, all five models show decreasing trends for both total CWW and CWC during the historical period, but most are statistically insignificant at the 95% significance level, with the exception of MIROC-ESM-CHEM (p = 0.018, Figs. A9 and A10). Future projections of CWW and CWC indicate consistent and significant increasing trends across all models ranging in magnitude from 4097 to 5489 m^3/year (Fig. A9) and 3277 to 4391 m^3/year (Fig. A10), respectively. This increase can primarily be attributed to a rise in cooling water withdrawal due to air temperature, affecting both the humidity ratio and enthalpy of air exiting the wet cooling tower (see Equation (1) in Methods).

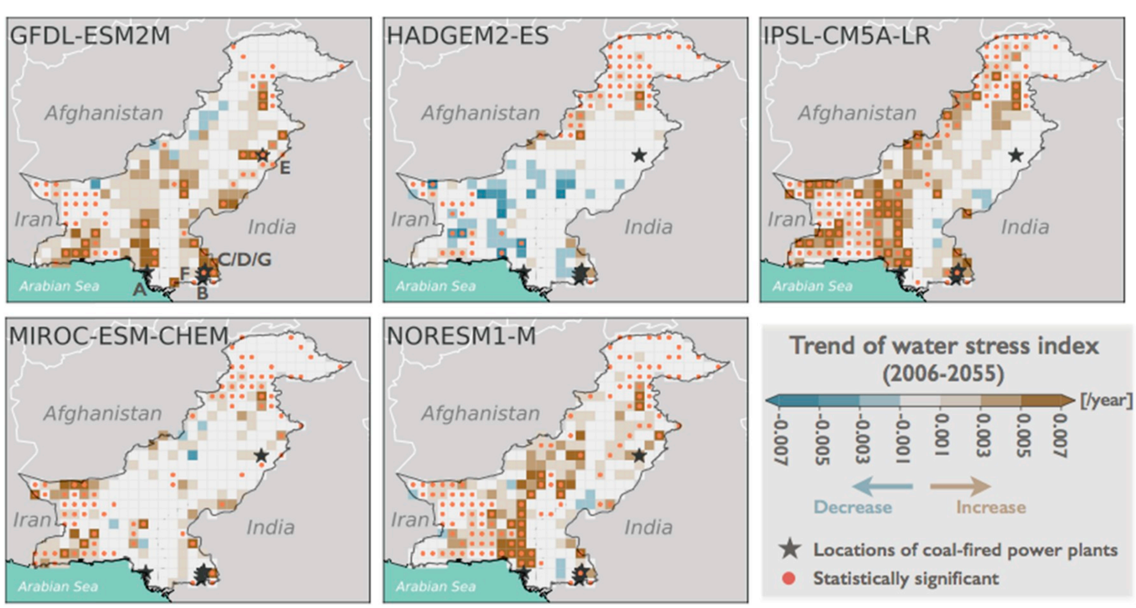

Fig. 3. Spatial distribution of the linear WSI trend in Pakistan from 2006 to 2055 projected by five GCMs under SSP2/RCP6.0. Orange dots indicate locations of statistically significant trends at the 95% significance level. Black stars indicate locations of power plants A–G (i.e., existing, under construction, and planned facilities financed by China). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

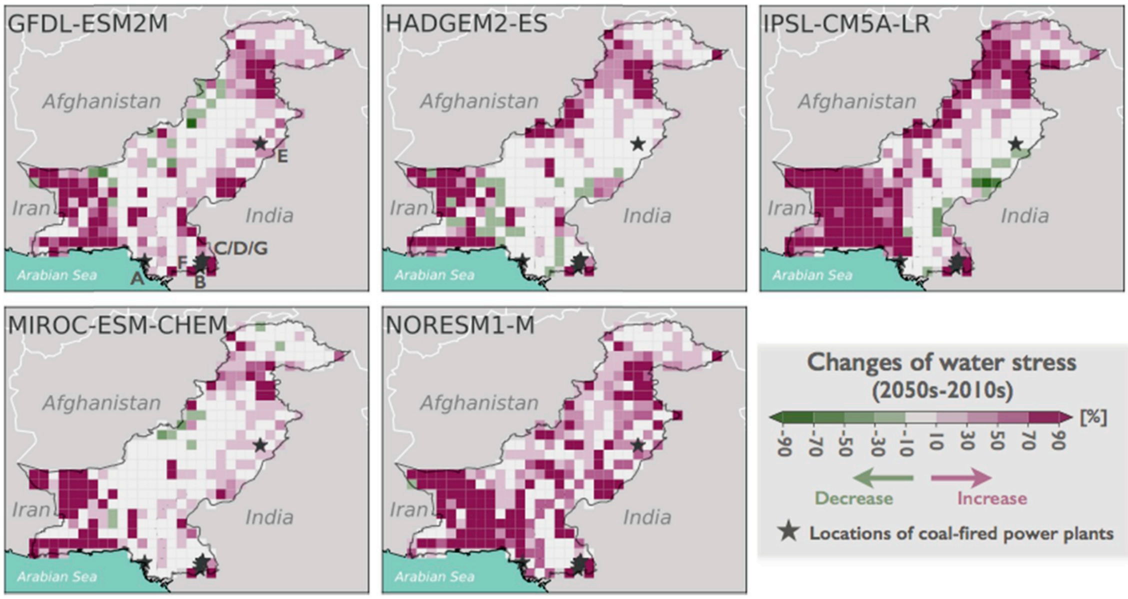

Fig. 4. Spatial distribution of relative WSI changes in the 2050s compared to the 2010s projected by five GCMs under SSP2/RCP6.0. Black stars indicate locations of power plants A–G (i.e., existing, under construction, and planned facilities financed by China).

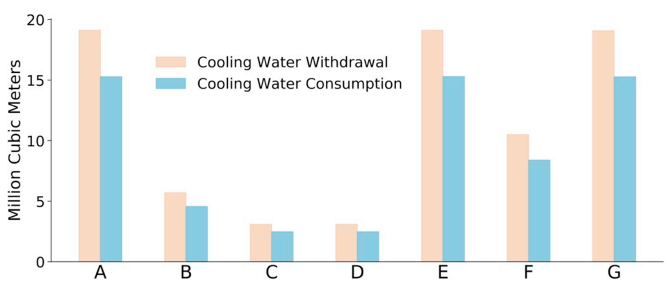

Fig. 5. Average magnitude of cooling water withdrawal and consumption for power plants A–G (in units of million cubic meters) in the 2050s (i.e., 2046–2055), where withdrawal and consumption are proportional to generation capacity and efficiency of the facility.

Fig. 5 depicts the total magnitude of CWW and CWC for each power plant from 2046–2055 based on the five climate models, including annual variations driven by both demand- and climate-related changes. From these calculations, the ensemble averages of annual mean CWW and CWC in the 2050s for plants A–G amount to 79.68 and 63.74 million m^3, or higher than the ensemble average streamflow locally in the 2050s (i.e., 37.54 million m^3).

Although WSI is calculated independently of CWW and CWC, as a measure of water availability, the former can help to contextualize the magnitude of the latter. In other words, WSI may provide a generalized understanding of how easily cooling water requirements will be met now and in the future. WSI values of the seven power plant locations already exceed 0.5 in the 2010s (Fig. 1) and are generally expected to increase into the 2050s (Fig. 3). Combining these WSI data with CWW and CWC calculations, it is clear that water scarcity and power plant water demands will increase simultaneously in the coming decades. In the case of extreme events (such as prolonged heat waves or drought), water availability will be a limiting factor impacting plant operation and generating capacity. We show that for all power plants, CWC under normal operating conditions (i.e., average capacity factor) is similar to or higher than the locally available annual mean streamflow (Fig. A11), indicating that other sources of water (e.g., groundwater, transported water from pipelines) will be needed to supplement surface water.

Under extreme operating conditions (e.g., full capacity factor, low streamflow as approximated by the lowest weekly averaged streamflow with a return period of 10 years), CWC usually far exceeds the locally available streamflow (Fig. A12), implying either interrupted power plant operation or increased demand on other water sources. Compound events (e.g., heat waves are oftentimes accompanied by droughts) will further magnify the predicted threat to regional and local water security, since CWC values more than double when assuming power plant operation at or near full capacity. Amplification of this threat would only be avoided at the expense of energy production. Even without considering climate extremes, however, the nearly 80 million m^3 of water required for just these seven coal-fired power plants to operate at capacity in the 2050s is staggering. This is especially true when considering alternative societal uses of water in Pakistan.

4. Discussion

The energy infrastructure proposed and established by BRI could reasonably impact sustainability and water security across much of Asia. In countries with an inadequate electric power supply, coal-fired power plants could promote SDGs related to enhancing livelihoods and eliminating poverty. In Pakistan, the total nameplate capacity of the seven coal-fired power plants studied here is 6600 MW, a significant contribution to nationwide power generation when considering the 4734–7053 MW deficit in Pakistan's peak electricity supply ("State of industry report. National Electric Power Regulatory Authority.," 2016; "State of industry report. National Electric Power Regulatory Authority.," 2015). Alleviation of the power deficit may improve the livelihoods of Pakistani households, which lost 195.8 billion Rupees (US $1.7 billion), or 16.8% of annual total consumption expenditure, to electricity outages in 2011 (Khan and Abbas, 2016; Pasha and Saleem, 2013; Tang and Shahbaz, 2013). Officials have cited BRI investments as a crucial factor contributing to Pakistan's high economic growth rate in 2017; the growth rate is expected to reach 7% in 2020 with the continuation of CPEC (CPEC, 2018).

However, the societal benefits from BRI's energy-facilitated poverty alleviation may be offset by negative impacts on other sectors, a phenomenon which has historically been observed in the context of foreign direct investments (Huang et al., 2017). In particular, heightened water stress related to climate change and power plant cooling has direct downstream effects on food security and indirect consequences for public health. Agriculture contributes 21.3% to the gross domestic product of Pakistan (Herani et al., 2007), and depletion of regional water resources impacts food production by decreasing irrigation area and crop yield. Unsurprisingly, this will threaten Pakistan's agriculture sector and impact low-income, rural communities at the local level. This outcome directly contradicts recommendations made following socioeconomic and demographic analyses of poor Pakistani populations. Namely, these studies tend to support agricultural expansion as well as the earmarking of more land to poverty-stricken households (Chaudhry et al., 2009).

Of course, BRI-financed coal plants are only one part of a complex and dynamic power sector. Moreover, the power sector represents only one of the major water users and consumes far less than some other sectors, such as agriculture. Water security and sustainability will require that attention be paid to all of these users. In emphasizing the water-energy nexus, this research complements, rather than sidesteps, existing scholarship documenting the effects of agriculture on water resources (e.g., Rasul, 2016; Shah, 2010). In the context of this nexus and the importance of agriculture in determining the future of water security in Pakistan and many other countries, we believe that considering energy infrastructure is necessary because of: (1) the additive, interactive nature of water stress; (2) the long-term nature of energy generation infrastructure investments; and (3) the fact that the BRI constitutes a critical juncture for infrastructure sustainability in many countries.

Besides threatening agriculture, construction of power plants will inherently reduce land supplies which could help lift rural residents out of poverty (Chaudhry et al., 2009), not to mention increasing the likelihood of food insecurity for these populations. These populations are frequently forced to choose between dehydration and consumption of non-potable water sources, or between water consumption and personal hygiene, when faced with water scarcity (Hunter et al., 2016). Historically, Pakistan, like many other developing countries in Asia, has suffered from poor water quality, underscored by the fact that 20–40% of patients in the nation's hospitals suffer from waterborne diseases (Azizullah et al., 2011). These are just a few examples of how future impacts on water stress are likely to have disproportionate effects; in fact, research in India suggests that the adverse impacts on water security resulting from foreign investment fall on the poorest and most vulnerable populations (Rudra et al., 2018).

Finally, decreasing water availability has the potential to exacerbate conflict and aggravate Pakistan's already acute security crisis. Research has pointed to the impact of water availability on conflict onset through mechanisms including aggregate economic growth (Miguel et al., 2004), livestock price shocks (Maystadt and Ecker, 2014), and food and water instability (Gleick, 2014). Conditions that make water stress-induced conflict more likely include ethnopolitical marginalization (Theisen et al., 2012) and a combination of group-based divisions and agricultural dependency (Von Uexkull et al., 2016); these conditions pertain to Pakistan as well as many other BRI-affiliated countries. Given current water stress, it is perhaps unsurprising that a dispute over Indus River water-sharing agreements heightened military tension between Pakistan and India in 2016. In the coming decades, enhanced water stress and regional competition for water resources will exacerbate political tensions and affect the security environment in Pakistan and around the world.

Furthermore, despite the expectation of positive economic growth directly related to BRI projects like coal-fired power installations, Pakistan is predicted to be one of the most high-risk BRI-participating countries in terms of debt potential. This means that Pakistan's current and projected GDP will be insufficient for paying off the debts associated with its local BRI projects, making the country unsustainably indebted to Chinese creditors (Hurley et al., 2018). This may counteract economic growth outcomes associated with more robust power supplies, resulting in decreased economic security and again threatening progress toward achievement of the SDGs. In sum, BRI's coal-fired power plants will have complex effects on different SDGs, which should be better incorporated into the planning processes of China and BRI destination countries.

5. Conclusions and policy recommendations

While the economic opportunities provided by BRI could be instrumental in lifting participating low-income nations out of poverty, the long-term impact of its energy projects deployed now or in the future may irreparably damage both local and global climate security. BRI is poised to inform the construction of new and refurbishment of existing infrastructure in many developing regions, multiplying its influence over environmental outcomes and the future of global sustainability (Ascensao et al., 2018).

That said, it is important to be circumspect about the extent to which we can generalize our findings to other countries, and we acknowledge that country-specific energy development plans, climate change impacts, and other variables could affect the energy-water nexus in complex ways. At the same time, Pakistan is one of many countries where BRI investments in coal-fired power have been planned or begun (Shearer et al., 2019). Many BRI destination countries face similar future water stress projections (Satoh et al., 2017), but there has been no or negligible integrated water-energy nexus planning to-date. Thus, while the outcomes of projections and analyses like ours are likely to vary across countries, they highlight the utility of such exercises for energy scholars and policy makers alike.

We also acknowledge that BRI is financing the establishment of some renewable energy-based facilities, including hydropower plants in the valleys of northern Pakistan. However, the fact remains that a large portion of the energy infrastructure proposed and under construction consists of coal-fired power plants, which have frequently been sited in areas already experiencing some degree of water stress. As such, it would be prudent to consider amending plans for energy infrastructure development in BRI destination countries, according to both the SDGs and projections of climate stresses over the coming century. Based on the results of this study, we recommend the following policy actions:

1. Future energy demands must be met by shifting the current distribution of energy sources from primarily coal-based to primarily renewables. Existing coal-fired power plants in BRI destination countries should be outfitted to maximize water use efficiency (i.e., super- or ultrasupercritical), while new energy projects should prioritize renewable, locally abundant power sources (e.g., solar, wind). Destination countries must implement more holistic and forward-looking regulations. At the same time, China's central government should push firms involved in developing coal-fired power overseas to match cooling technologies with local water availability, much like China has attempted domestically. This will bring China's actions in-line with stated goals for a “Green Belt and Road,” which it publicly promoted at its most recent (i.e., April 2019) Belt and Road Forum.
2. Allocating resources in a water-scarce future requires a complete understanding of current water uses across neighboring regions. BRI should facilitate the establishment of programs to track water use across all sectors and borders, providing data to inform policies allocating water to energy production, among other uses. Community resilience in the face of water scarcity requires that new sources of water be exploited. Regional facilities implementing technological advancements in water treatment (e.g., desalination plants, water capture facilities, groundwater banking systems) should be financed by BRI to increase the supply of potable water across borders. Similarly, as indicated by the project-level water stress values, it is important to consider the sustainability and water security implications at different scales, including highly localized impacts.
3. Economic and social development must be facilitated with recognition of persistent global challenges, including climate change and associated water stresses. Systems involving food production,

healthcare, and local economies within BRI destination countries and beyond must be sustainable in order to promote long-term realization of proactive policies.

It is predicted that these recommendations would help ensure an adequate and thriving energy supply, while also considering the many demands placed on limited water resources. Our case study of Pakistan shows that regional water stresses will increase even before considering new water demands, including those imposed by climate changes. Furthermore, this demand will be substantially increased by the new requirements of existing and planned energy generation facilities. Our analysis of BRI-affiliated coal-fired power plants under the RCP6.0 climate scenario suggests a substantial demand for total cooling water from Chinese-financed plants that would reduce water availability for all other uses in the region.

Water demands at odds with one another must be addressed before conflicts arise, especially in places like Pakistan where tensions over water availability already threaten geopolitical stability (Sinha, 2010). Therefore, strategic distribution of resources in a water-insecure future is crucial, and sustainable development of energy facilities requires working within, rather than placing unnecessary stresses on, water allocation frameworks. As an in-progress development framework of unprecedented size, BRI provides a unique opportunity for consideration of interconnected climate, energy, and societal concerns, with the potential to profoundly influence global sustainability planning into the next century.

Author contributions

M.A., X.H., A.R.P., W.L, and T.H. conceived the research and drafted the manuscript. X.H. performed the analysis with help from Y.W. N.W. provided streamflow temperature data. All authors discussed the results and contributed to the final written product.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2019.06.044.

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