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TECHNICAL COMMUNICATION

Spatial Relationships of Water Resources with Energy Consumption at Coal Mining Operations in China

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Abstract
The spatial characterization and regional differences of water use in China's coal mines were investigated based on a high spatial resolution mine site dataset, and their spatial synergic relationships with energy consumption were explored using a geographic weighted regression model. There were significant and obvious regional differences in water use in coal production. Most coal-related water withdrawal occurs in Shandong, Henan, Hebei, Anhui, Shanxi, Shaanxi, and Inner Mongolia provinces, accounting for ≈ 73% of the nation's total energy-related water withdrawal. The cities of Erdos, HulunBuir, Yulin, Shuozhou, and Changzhi have the largest coal-related water consumption, ≈ 36% of the nation's total, while large coal-related wastewater discharges are mostly concentrated in Shaanxi, Hebei, Shanxi, Henan, and Inner Mongolia provinces, and sporadically in Guizhou Province. There was a considerable positive correlation between consumptive water use and energy consumption in coal production. This study provides a spatially integrated technology to coordinate regional energy and water plans, identify regions suffering the most severe impacts, and can serve as a reference for the transition of coal resource-type cities.

Keywords Water use · Sustainable energy and water · GWR model

Introduction

The energy sector is the second largest water user in the world in terms of withdrawals, following only irrigation (Hightower and Pierce 2008). China was the world's largest energy producer and consumer in 2014 (Yi 2014), and its ever-increasing energy supply and energy consumption provide important support for its economic and social development. These increases contribute to increased CO_2 emissions and consume a vast quantity of water (Li et al. 2012; Lin et al. 2017). China has 6% of the world's freshwater resources, but the per capita water availability (≈2100 m^3) is less than a quarter of the world average (Guan and Hubacek 2008), and energy-water nexus issues have become increasingly prominent. To address this situation, the country is committed to developing alternative energy strategies for water conservation, including wind and solar energy (Lewis et al. 2015).

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Coal mining and coal washing consume a vast quantity of water, and coal mines are usually accompanied by mine drainage during production, which can cause severe environmental pollution for both surface and ground water. Coal remains China's top source for electricity and will continue to increase its share in the short term (Lin et al. 2018). According to the IEA (2018) report, China's coal consumption will still account for ≈ 55% of energy resource consumption in the year 2022. Zhang and Anadon (2013) systematically estimated the life cycle water withdrawals, consumptive water use, and wastewater discharge of China's energy sectors (including the coal industry) and their water consumption-related environmental impacts using a mixed-unit multiregional input–output (MRIO) model and life cycle impact assessment method (LCIA). Shang et al. (2016) quantitatively analyzed synergies between energy consumption and the water supply in China using a holistic approach and evaluated the effects of the coal consumption cap strategy on water conservation in major industrial sectors. These studies provide an essential reference for further research on the energy-water nexus in coal production.

In addition, the endowments of coal and water resources in China appear to be inversely distributed in space, and large coal industry bases are located in the north and center-west regions, which bear the worst water shortages. For instance, the Jin-Shan-Meng-Ning-Gan District (JMG) produces more than 60% of China's coal, but has less than 5% of its water resources. The development of coal power and the coal chemical industry there causes serious challenges for the security of the region's water resources and the environment.

Scholars have attempted to apply high-resolution spatial analyses to understand and address water problems associated with the thermal power industry in the United States (Clemmer et al. 2013; Yates et al. 2014). Zhang et al. (2016) also investigated the spatial distribution of water withdrawal and consumption by thermal power generation and associated water stress at the catchment level in China based on a high-resolution geodatabase of electric generating units and power plants. However, existing studies have focused mostly on the thermal power industry, and coal production-based water use studies are limited, largely because of insufficient high spatial resolution data. Previous research has shown that most Chinese cities have water shortages, and up to 40% of rivers are severely polluted (Ministry of Science and Technology of the People´s Republic of China 2007). For this reason, water use for energy production should be characterized in as much detail as possible to assess the potential of different policy approaches for water conservation.

This study aims to quantify the impact of coal mining operations on water resources from the perspective of water use at the prefecture-level administrative level to analyze their spatial characterizations and regional differences based on high spatial resolution data. Moreover, the spatial synergistic relationship between water use and energy consumption in coal mining is explored using the geographic weighted regression (GWR) model. It should provide aid policy-makers in China to formulate region-specific energy policy.

Data Acquisition

Productive Coal Mines of China

Production data for 3373 operating coal mines in China from 2018 were obtained from the National Energy Administration of China (NEAC), including information on annual production and geographic location (NEAC 2019). Annual production was attributed to one of 197 cities (defined as prefecture-level administrative units in China), based on the geographic location of the mines. The country was divided into five regions for the purposes of this study based on their geological conditions, the exploitation and utilization technology of coal mining, and the administrative districts (Fig. 1), including the Xin-Qing (XQ), North-east (NE), East China (EC), South China (SC), and JMG districts.

Coal Production-based Energy Consumption

In this study, the coal production-based comprehensive energy consumption at the provincial level was estimated, and then the comprehensive energy consumption per unit coal production was calculated in each province. Finally, energy consumption at the prefecture-level scale was estimated by multiplying the annual production by the comprehensive energy consumption per unit coal production (Fig. 2).

Methodology

Impact on Water Resource at Mining Operations

This study focuses on the life cycle water use of coal production in China. The freshwater withdrawals (WCW), consumptive water use (WCC), and wastewater discharge (WWD) were systematically quantified. The commonly used water use factor (WUF) method adopted in this study estimates water use by setting the WUF of the energy and multiplying it by production, as described in the following equations:

$$WCW = P_{coal} \times F_{withdrawal} \tag{1}$$

$$WCC = P_{coal} \times F_{consumption} \tag{2}$$

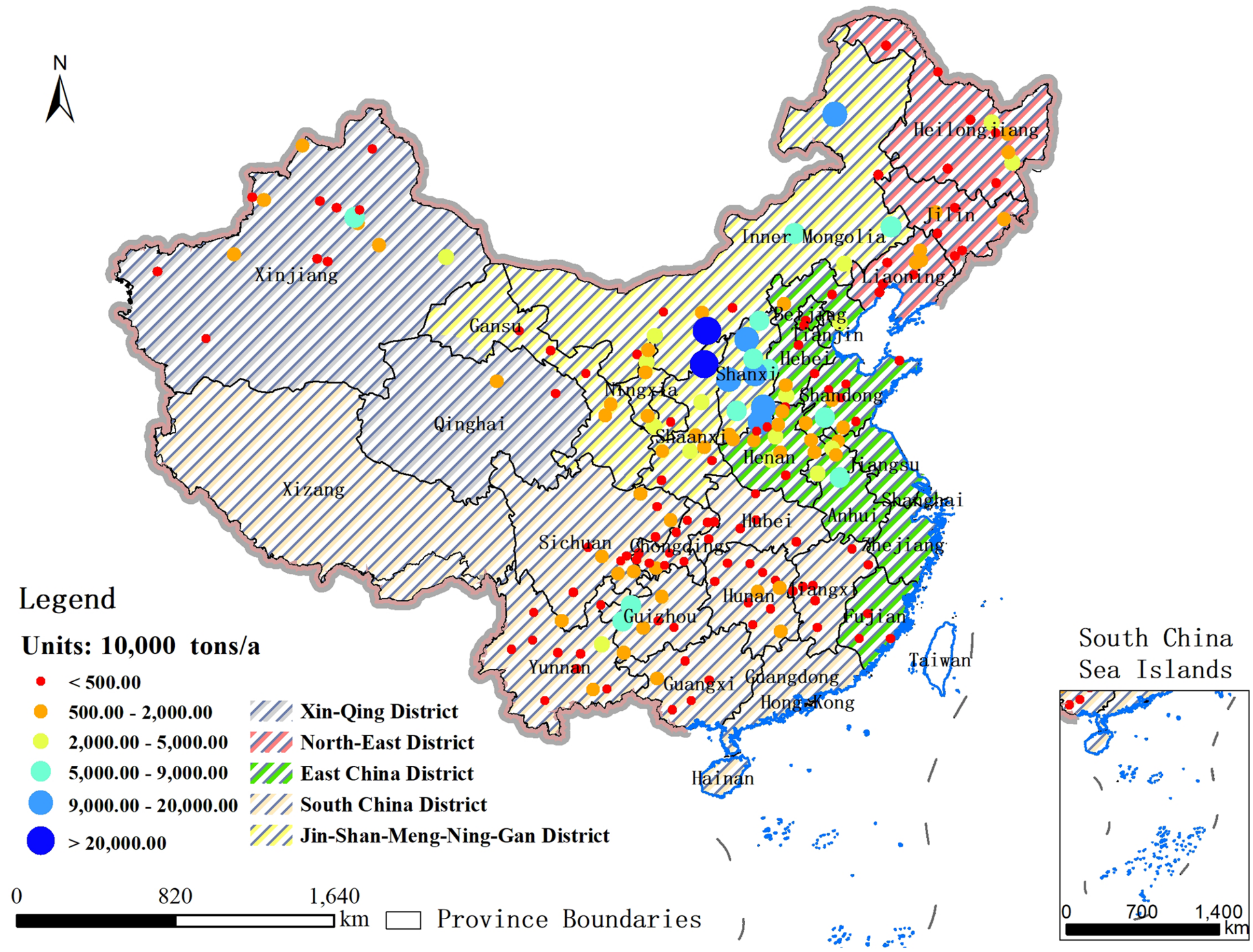

Fig. 1 Coal production of 3373 operated coal mines in 197 Chinese cities

$$WWD = P_{coal} \times F_{discharge} \tag{3}$$

where P_{coal} is the coal production; and $F_{withdrawal}$, $F_{consumption}$, and $F_{discharge}$ represent the coefficients for WCW, WCC, and WWD, respectively. The water withdrawal, water consumption, and wastewater discharge coefficients in each province used in this study were referenced by Zhang and Anadon (2013; data source: https://pubs.acs.org/doi/abs/10.1021/es402556x).

Spatial Autocorrelation Analysis

Numerous geographic phenomena are spatially auto-correlated and influenced by spatial interaction and expansion; spatial autocorrelation is a statistical method used to measure the interdependence of geographic data based on the theory of the continuity of spatial processes in their geographical distributions (Miron 1984). There are usually two ways to implement spatial autocorrelation, i.e. a global model and a local model. Global spatial autocorrelation describes the holistic distribution characteristics of geographical phenomena and assesses the agglomeration in terms of the spatial distribution (Moran 1950), while local spatial autocorrelation explores the distribution pattern of individual element attribute values in a heterogeneous space and can measure the degree of local spatial correlation between each area and its surrounding areas (Anselin 1995). To investigate the spatial characteristics of coal production water use, the global Moran's I tool (Eq. 4) was applied.

$$I = \frac{n}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \cdot \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}\left(x_i - \bar{x}\right)\left(x_j - \bar{x}\right)}{\sum_{j=1}^{n}\left(x_i - \bar{x}\right)^2} \tag{4}$$

where I represents the global Moran's I, n is the total number of study areas, x_i and x_j stand for the values of attribute feature x at regions i and j respectively, w_{ij} is an element of

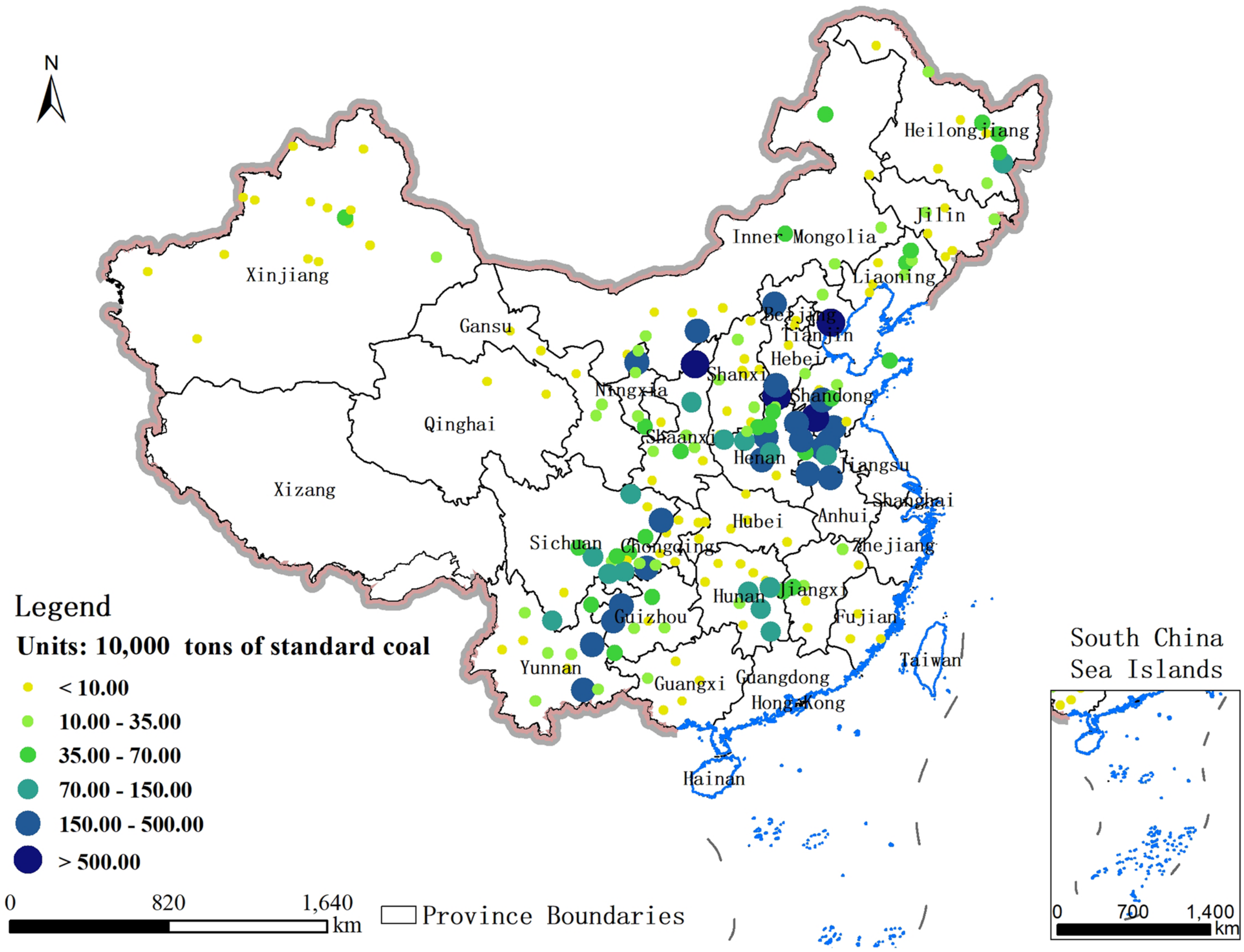

Fig. 2 Coal production-based energy consumption in 197 Chinese coal cities

the space weight matrix, w, used to express the neighboring relationship of the spatial regions at n positions, and $\overline{x}$ is the average of all observations for an attribute feature, x, in n study areas. The global Moran's I values vary from -1 to 1, and the closer that the value is to -1 or 1 represents more obvious spatial characteristics. When Moran's I is greater than 0, it indicates a positive variable correlation, and values less than 0 indicate a spatially negative variable correlation.

Spatial Relationships with Energy Consumption at Mining Operations based on the GWR Model

The GWR model is a spatial analysis technique that was developed to explore spatial heterogeneity by inserting the spatial locations of regression parameters in the regression model (Fotheringham et al. 2001). The model considers the local estimates of the parameters by building the local form of linear regressions and investigates the impact of independent variables on the dependent variables with changes in locations (Brunsdon et al. 1998). This model has been extensively used in numerous fields, such as epidemiology (Li et al. 2017), management (Soler and Gemar 2018), soil pollution (Perugini et al. 2012), air pollution (Lin et al. 2015), and social sciences (Lin et al. 2014).

$$y_i = \delta_0\left(\alpha_i, \beta_i\right) + \sum_k \delta_k\left(\alpha_i, \beta_i\right)x_{ik} + \theta_i, (i = 1, 2, \ldots, n) \quad (5)$$

where $\left(\alpha_i, \beta_i\right)$ represents the spatial coordinates of sample point i, and $\delta_k\left(\alpha_i, \beta_i\right)$ represents the regression coefficient of sample point i. θ_i is the random error of the independent distribution, which is usually assumed to obey a normal distribution (Fotheringham et al. 2001). The bandwidth is an important parameter for the GWR model to control the degree of smoothing; an adaptive kernel with a bandwidth was chosen in the present study to minimize the corrected Akaike information criterion (AIC) by evaluating the spatial configuration of the features.

Results and Analysis

Water Use at Mining Operations and Their Characteristics

Figure 3 shows the spatial distribution of the withdrawals, consumption, and wastewater discharge related to consumptive water use associated with coal production in China in 2018. Regional differences in coal production-based water use are significant and obvious, especially for water withdrawals and wastewater discharge. Most coal-related water withdrawals occur in the EC (mainly distributed in Shandong, Henan, Hebei, and Anhui provinces) and JMG (mainly distributed in Shanxi, Shaanxi, and Inner Mongolia provinces) regions of China. The water withdrawals in the above provinces are 141.21, 85.75, 70.68, 70.49, 246.99, 63.66, and 111.98 million m^3, respectively, which account for ≈73% of the national total energy-related water withdrawals. Cities in Jining of Shandong, Erdos of Inner Mongolia, Yulin of Shaanxi, Shuozhou and Changzhi of Shanxi, and Huainan of Anhui occupy the top six places, with energy-related water withdrawals of more than 30 million m^3. These cities are all distributed in regions with serious water-bearing capacity overloads (Liu et al. 2011), where coal-related water withdrawals cause additional water resource stress.

The spatial distribution of coal-related water consumption differs tremendously from that of water withdrawals, and most coal mines in EC consume less water resources than is withdrawn. From the perspective of space, there is generally an inverse pattern between the spatial distributions of water consumption and freshwater resources in China. The top five cites with the largest coal-related water consumption are Erdos (112.25 million m^3) and HulunBuir (19.10 million m^3) of Inner Mongolia, Yulin (66.46 million m^3) of Shaanxi, and Shuozhou (27.55 million m^3) and Changzhi (21.37 million m^3) of Shanxi, which together account for ≈36% of the national total. Most areas of these cities

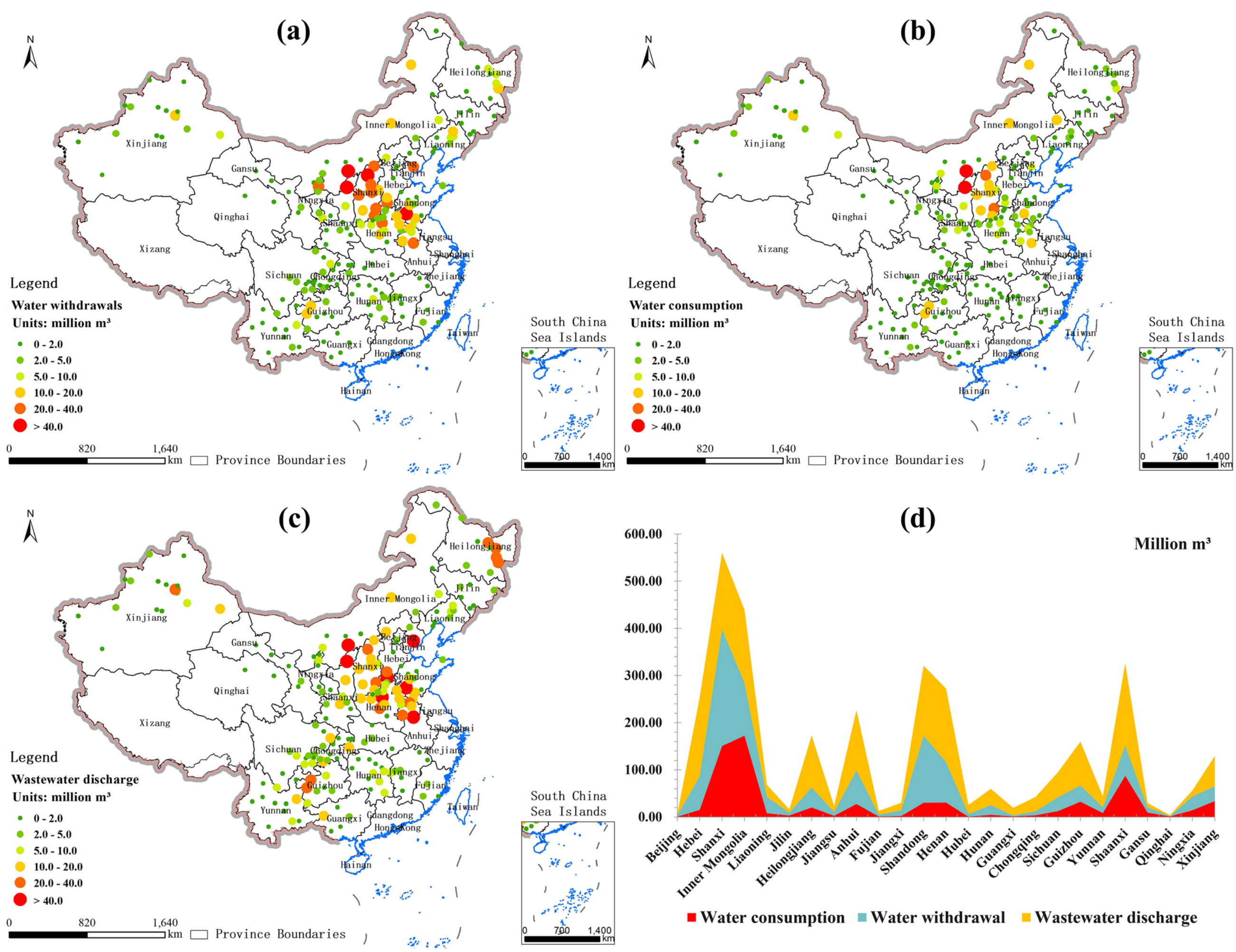

Fig. 3 Spatial distribution of withdrawals, water consumption and wastewater discharge related to consumptive water use [water withdrawals (**a**), water consumption (**b**), wastewater discharge (**c**)] of coal production in China in 2018. *Note* **d** is the provincial coal production-based water use

are located in arid and semi-arid areas in northwest China, where the most severe water shortage problems and water environment deterioration occur.

The spatial distribution of wastewater discharge is quite similar to that of water withdrawal, but the situation is more severe than that of coal-related water withdrawals in SC. Large volumes of mine drainage are generated and discharged during the coal mining process, causing the wastewater discharge intensity to exceed its direct water withdrawal intensity (Zhang and Anadon 2013). The regions of large coal-related wastewater discharge are mostly concentrated in JMG and EC (mainly in Shaanxi, Hebei, Shanxi, Henan, and Inner Mongolia provinces), but sporadically occur in Guizhou Province, such as in Liupanshui and Bijie, which indicates that a large amount of mine water is discharged during coal mining in these regions. Therefore, it is essential for mining cities to alleviate water resource deficits by promoting the use of mine water.

Table 1 shows Moran's I values for withdrawals, water consumption, and wastewater discharge related to consumptive water use of coal production: 0.26, 0.14, and 0.12, respectively, which indicate a significant positive spatial autocorrelation in consumptive use of coal production water. The water withdrawal data are most influenced by spatial interaction and expansion, while the wastewater discharge data are the weakest. To further understand spatial influences on the consumptive water use of coal production at the city level in China, we used the GWR model to explore their synergistic relationships with the energy consumption of coal production.

Spatial Relationship with Energy Consumption at Mining Operations

According to the results of this operation, the R^2 values from the GWR model were 0.82 (water withdrawals), 0.73 (water consumption), and 0.94 (wastewater discharge), which revealed considerable correlation between consumptive water use and energy consumption in coal production. In this study, the $f = \frac{V_{GWR}}{RSS_{GWR}}$ (V_{GWR} represents the variance of the coefficients, and RSS_{GWR} represents the residual sum of squares), as an f statistic, was built to examine the spatial instability of the regression coefficients of each variable using an F-test, based on the method of Leung et al. (2000). The ratios between f and the corresponding degrees of freedom for each variable are more than the critical value at the level of 0.05, indicating that the spatial variation in the regression coefficients of the variables was non-stationary.

Figure 4 shows the spatial coefficient distribution for the synergistic relationship between consumptive water use and energy consumption from the GWR model. The local coefficients in the water withdrawal model indicate that the influence of energy consumption on water withdrawals varies considerably; ≈ 98.95% of the study area had a positive correlation between these parameters. The positive correlations with the coefficients appeared in most regions of the country, but the highest correlations were mainly concentrated in SC. This is largely caused by the large number of small-production-scale coal mines in that region and the low level of mechanization, which brings both high energy consumption and high withdrawals. The spatial distribution of the local coefficients of water consumption varied considerably over the entire country, with a southeast-northwest orientation; ≈ 94.76% of the study area exhibited a positive correlation between energy consumption and water consumption. Similar to the water withdrawal situation, the high correlations were mostly observed in Jiangxi, Chongqing, Hunan, Shandong, and Anhui provinces, while low values occurred in the JMG and XQ regions, indicating that water consumption for mining might be combined with large potential energy consumption in the EC and SC coal mines. The maximum R^2 value was obtained from the GWR wastewater discharge model, which indicated a strong relationship between energy consumption and wastewater discharge. The local coefficient indicates that there were significant positive correlations between energy consumption and wastewater discharge around the country (Fig. 2c). However, it is worth noting that little correlation was observed in most of the XQ. This is because most coal mining in Xinjiang Province is by opencast mining (Song 2015), and the low water discharge pressure drives low energy consumption for drainage systems compared to the underground mining that occurs in most of JMG, EC, SC, and NE.

Table 1 The returned results of spatial autocorrelation analysis for water use of coal production

	Water withdrawals	Water consumption	Wastewater discharge
Moran's I	0.26	0.14	0.12
Z score	14.23	9.26	6.89
P values	0.00	0.00	0.00

Research Limitations

The objective of this paper was to investigate water use in coal production at the prefecture-level administrative level and to analyze their spatial characterizations and regional differences based on high spatial resolution coal mine data. The spatial synergistic relationship between them and the energy consumption in coal mining was also discussed using the GWR model. However, there are still two limitations to this study. The spatial pattern and regional differences for the water used in energy

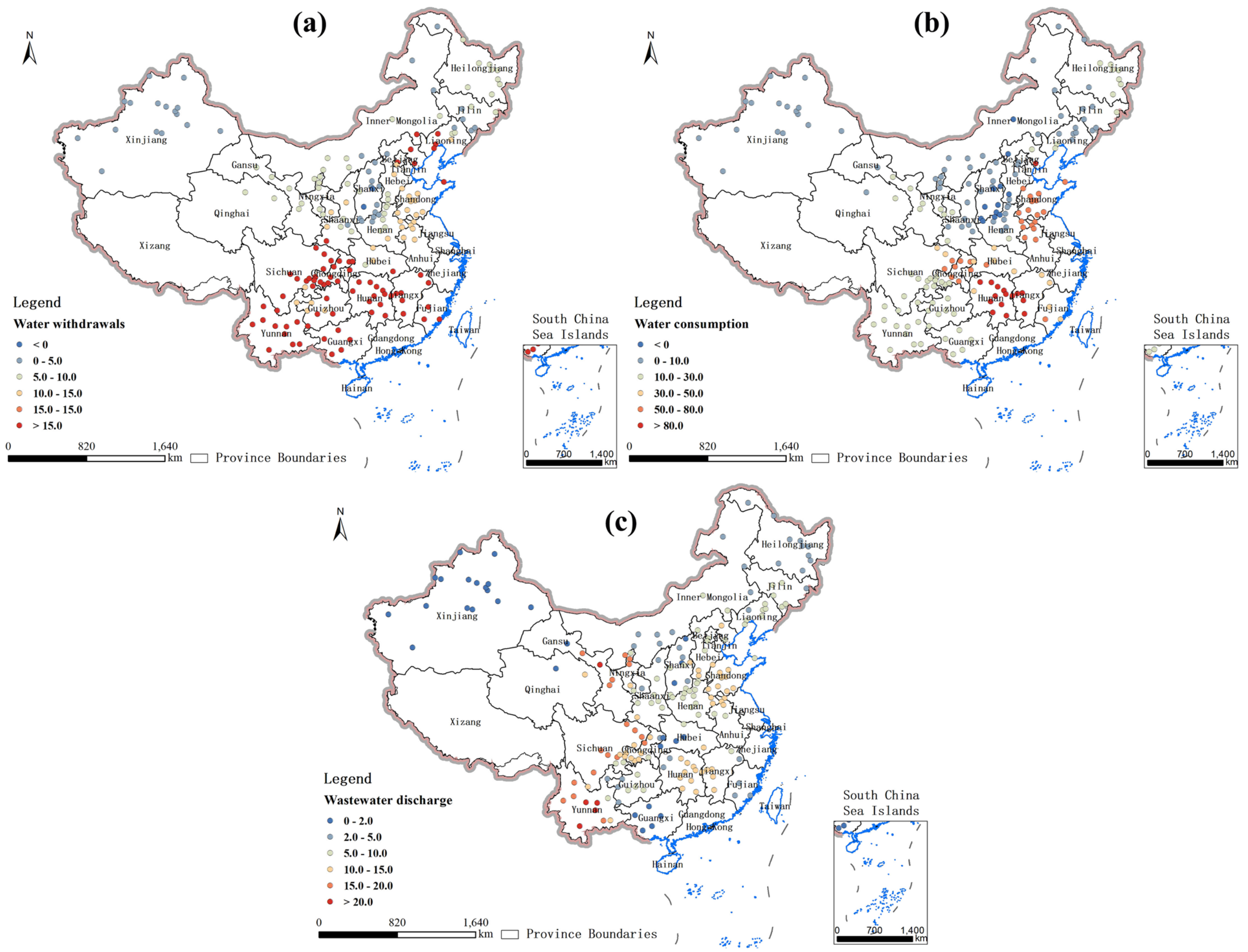

Fig. 4 The spatial coefficient distribution for synergic relationship between the consumptive water use with energy consumption based on the GWR model: **a** water withdrawals, **b** water consumption, **c** wastewater discharge

production is the combined result of many factors, such as geographical elements, production conditions, and geological conditions. This paper mainly focused on their synergistic relationships with energy consumption (a synthesized indicator that reflects the above factors), and cannot accurately diagnose the multi-factor driving mechanism of water use in coal production. More research is needed if relevant and detailed data can be obtained. Another limitation was the timeliness of the data. The coefficients for water withdrawal, water consumption, and wastewater discharge of coal production in each province referenced the study by Zhang and Anadon (2013), and the data might be mismatched in time with the coal production data in this study. If reliable data become available, future work will improve.

Conclusions and Discussion

In this study, the spatial characterizations and regional differences in water use in coal production were investigated, and their spatial synergistic relationships with energy consumption were explored based on the GWR model. The main conclusions are as follows:

There are significant and obvious regional differences in water use in coal production, especially for water withdrawals and wastewater discharge. Most coal-related water withdrawals occur in the cities of Shandong, Henan, Hebei, Anhui, Shanxi, Shaanxi and Inner Mongolia provinces, China, accounting for ≈73% of the national total energy-related water withdrawal. There is generally an inverse pattern between the spatial distribution of water consumption and freshwater resources in China, and the top five cites, Erdos, HulunBuir, Yulin, Shuozhou and Changzhi, with the largest coal-related water consumption occupied ≈ 36% of the national total. Due to the large volumes of mine drainage generated during the coal mining process, wastewater discharge exceeds water withdrawal in most underground coal mines. High coal-related wastewater discharge is mostly concentrated in Shaanxi, Hebei, Shanxi, Henan, and Inner Mongolia provinces but sporadically occurs in Guizhou Province. Our empirical findings suggest that the coal cities are most distributed in regions with a severe water-bearing capacity overload, and coal-related water withdrawals cause additional water resource stress. The formation of energy policy in mining cities should be more concerned about the utilization of mine drainage to alleviate water resource deficits, because a large amount of mine water is discharged during coal mining in these regions.

There is a significant positive spatial autocorrelation in the consumptive water use of coal production in China. The water withdrawal data are most influenced by spatial interaction and expansion, while the wastewater discharge data are the weakest. Moreover, according to the results of the GWR model, significant positive correlations exist between energy consumption and use of coal mine produced water in most of the country. Specifically, it can be inferred that the vast amounts of small-production-scale coal mines with low levels of mechanization in southwest China might account for both the high energy consumption and high withdrawals. Most coal mining in Xinjiang Province is by opencast mining, and the low water discharge pressure drives low energy consumption for drainage systems compared to underground mining in most of JMG, EC, SC, and NE.

In summary, coal production is a major component of China's water scarcity challenge. This study provides a spatially integrated method that allows a better understanding of the spatial coupling characteristics of water use in coal production. Additionally, it identifies regions suffering the most severe impacts, which can be used to coordinate regional energy and water plans and serve as a reference value for transition of coal resource-type cities.

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