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Energy consumption due to groundwater pumping for irrigation in the North China Plain

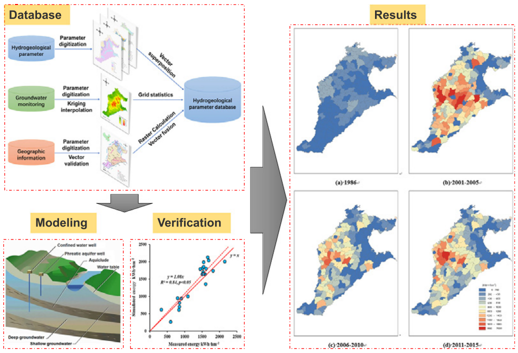
Xiuzhi Chen [a], Kelly R. Thorp [b], Zhiyun Ouyang [c], Yue Hou [a], Bo Zhou [d], Yunkai Li [a,*]

[a] College of Water Resources and Civil Engineering, China Agricultural University, Beijing, China
[b] USDA Agricultural Research Service, 21881 N Cardon Ln., Maricopa, AZ 85138, USA
[c] Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, China
[d] College of Agricultural and Life Sciences, University of Wisconsin-Madison, Madison, WI 53706, USA

HIGHLIGHTS

- The North China Plain is the largest energy consumption area for irrigation over world.
- A distributed pumping energy model for groundwater irrigation (DPE_GI) was proposed.
- This model can estimate the energy consumption of groundwater irrigation at county level.
- Groundwater condition, planting and climate influence irrigation energy consumption together.

GRAPHICAL ABSTRACT



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ABSTRACT

Irrigated agriculture consumes a large amount of groundwater resources with a huge energy requirement, and this has seriously restricted the development of green and efficient agriculture in China. However, recent studies on energy consumption for irrigation focus mainly on individual irrigation systems or single wells, and few spatial-temporal energy assessments have been carried out at regional scale. This is needed for effective management of regional energy consumption for groundwater utilization. Based on single-well pumping method, a distributed energy consumption model for groundwater irrigation (DPE_GI) was proposed in this study. The North China Plain (NCP) was selected as the research area, which is a typical groundwater irrigated area and has severe issues with aquifer depletion. The results showed that the average annual energy consumption for groundwater pumping was 13.67 billion kW h, and the energy consumption per area was 1122.4 kW h hm^{-2} under the winter wheat - summer maize rotation system in NCP. Current groundwater pumping energy consumption in the NCP is 2.9 times of the initial value in 1986, and the NCP has already become the world's largest energy consumer for groundwater irrigation. Due to the uncertainty of precipitation, energy consumption for irrigation fluctuates per growing season. Groundwater level also impacts energy consumption. Popularizing water-saving irrigation technology such as drip or sprinkler irrigation, changing cropping systems and habits can effectively reduce energy consumption for irrigation.

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[*] Corresponding author at: College of Water Resources and Civil Engineering, China Agricultural University, No. 17 Tsinghua East Road, Beijing 100083, China.
E-mail address: yunkai@cau.edu.cn (Y. Li).

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1. Introduction

With the development of modern agricultural practices for grain production, the quantity of irrigated farmland has increased rapidly (Dalin et al., 2017), and the demand for irrigation water has increased exponentially in past 70 years due to population growth and increasing food requirements (Trivedi et al., 2001). Global groundwater withdrawal increased from 100–150 km^3 to 950–1000 km^3 from 1950 to 2010 (FAOSTAT, 2014). While irrigation increases water supply for crop production, it consumes a large amount of electrical energy or fossil fuel energy for the process of water lifting, thus leading to resource and environmental costs (Wada et al., 2012). With increased focus on resource limitations and environmental problems such as global warming (Kerr, 2006, 2012), more attention has been paid to the energy consumption concomitant with irrigated agriculture. With the severe over-exploitation of groundwater in recent years, the aquifer water depth has been declining steadily, and the energy consumption for irrigation has increased exponentially (Smidt et al., 2016; Wang et al., 2012). At present, almost all major regions that rely on groundwater resources for irrigation are facing huge limitations in available energy supplies (Dahlberg, 2000). Smallholder irrigated agriculture and poor management are important causes of this phenomenon, especially in south Asia, the western United States, and northern China (Dinar, 1994; Rodell et al., 2009). Therefore, it is necessary to estimate energy consumption required for irrigation in these areas and to effectively manage the size of the irrigated area for agricultural energy conservation, emission reduction, and improvement of irrigation efficiency.

Irrigation that relies on groundwater is one of the most energy consuming irrigation methods (Mukherji, 2007). To further understand the energy consumption of this irrigation method, many scholars have carried out research on energy consumption for such irrigation systems. By analyzing the relationship between irrigation and energy in south Asia, improvement and protection of groundwater was shown to effectively improve energy capacity and power security (Shah et al., 2007). The energy input requirements for central pivot overhead sprinkler irrigation systems and for conventional and drip irrigation have been analyzed (Nasseri, 2019; Rao et al., 2018), and the studies found that irrigation accounted for a large proportion of energy needs. The energy consumption and greenhouse gas emissions due to irrigation systems were studied by the life cycle method and found that irrigation using groundwater resources consumed more than using surface water (Acharya et al., 2015). Some scholars comprehensively analyzed the energy use for pumping groundwater for irrigation in an arid region of Syria and provided a basis for management of regional energy consumption (Gul et al., 2005). However, the lack of data and studies at the scale of irrigation regions makes it difficult to solve energy problems at regional or basin scales. One study estimated the irrigation energy consumption of the NCP (Qiu et al., 2018), but it did not consider the hydrogeological conditions and changes over years, and the accuracy of the calculation needs to be further improved. Due to the lack of energy consumption data for irrigation, the accuracy of current studies assessing irrigation energy requirements is poor, which makes it difficult to effectively manage large irrigated areas from a regional perspective. Counties are the most basic administrative units in China and also the smallest administrative level to realize effective statistics. The study of irrigation energy consumption at county level can provide an accurate and reliable basis for regional energy consumption regulation and management.

The objectives of this study were to (1) propose a distributed energy consumption model for groundwater-based irrigation systems (DPE_GI) using a single-well approach, (2) understand the temporal dynamics of energy consumption for irrigated agriculture in the North China Plain (NCP), (3) explore the driving factors of regional irrigation consumption, and (4) design strategies for agricultural water-energy management and food security in the NCP and beyond.

2. Methods

2.1. Study area

The NCP is one of the world's largest areas utilizing groundwater resources for irrigation and has developed into the world's largest groundwater user due to continuous over-extraction (Cao et al., 2013; Yuan et al., 2013). It is located in the east of China (112°30′E~119°30′E, 34°46′N~40°25′N) as shown in Fig. 1. It covers all the plains of Beijing, Tianjin, Hebei and the north plain of the Henan and Shandong provinces. The total area of the study region is about 0.13×10^6 km^2 and consists of 207 counties. The total cultivated land in the region is 0.021×10^6 km^2, accounting for 11.7% of total land area under agricultural production in China. Total grain production reaches 70 million tons, accounting for 15% of total China production. About 80% of the cropped area is used for grain production, and winter wheat and summer maize are both widely planted, accounting for 50% and 46% of the region respectively (Wang, 2010). The population of the NCP has increased from 97 million in 1980 to 150 million in 2016 (+54.6%) (Kang and Eltahir, 2018). As a result, the water resources per capita have notably decreased, and the contradiction between development and water is exacerbated.

Rainfall in NCP is spatially variable, and the precipitation in winter wheat growing period cannot meet the crop water requirement. Due to the shortage of surface water resources, most areas rely on groundwater wells for irrigation. For example, in the Hebei Plain, 72% of irrigation water for grain production comes from wells (Hu et al., 2010). From 2000 to 2005, the average annual irrigation water consumption was 146.8×10^8 m^3 yr^{-1} in NCP, accounting for 70.6% of the total water consumption. Groundwater is the main water supply source for irrigation, which accounts for >79% of water used for irrigation.

2.2. Distributed energy consumption model of groundwater irrigation (DEG_GI)

2.2.1. Model assumption

In this paper, a distributed energy consumption model of groundwater pumping for irrigation was composed of two parts: the energy consumption model for groundwater pumping and the distributed model. To ensure the reliability of the model and reduce uncertainty, the following assumptions were made:

(a) The amount of irrigation water pumped was assumed equal to the water consumption of crops during the growth period minus effective rainfall, and the water consumption of crops over the entire growing season was calculated based on crop yield and water productivity function.

(b) Water pumping was considered as a constant flow from a single well. After the unsteady movement of water in the initial stage, the size of the cone of depression grows slowly with time, and the groundwater reaches a steady state (Brown and Burges, 1973). Due to the large spatial scale of the study region, the influence radius method cannot be used to estimate the amount of water extracted before the steady condition reached. The changes of groundwater level caused by irrigation recharge is not taken into account, this paper considers that the observed groundwater level is stable in the pumping process. A schematic diagram of groundwater pumping from a single well for different aquifers is shown in Supplementary information Fig. 1.

(c) Because the vast majority of pumps in China are powered by electricity rather than fuel, the pump efficiency was assumed to be 40% (Mao et al., 2005). According to the investigation, the traditional irrigation methods such as furrow and border irrigation are mostly used in the NCP. Low-pressure pipelines were assumed for transfer of water with little kinetic energy, which accounted for about 0.14% of the total energy and could be ignored.

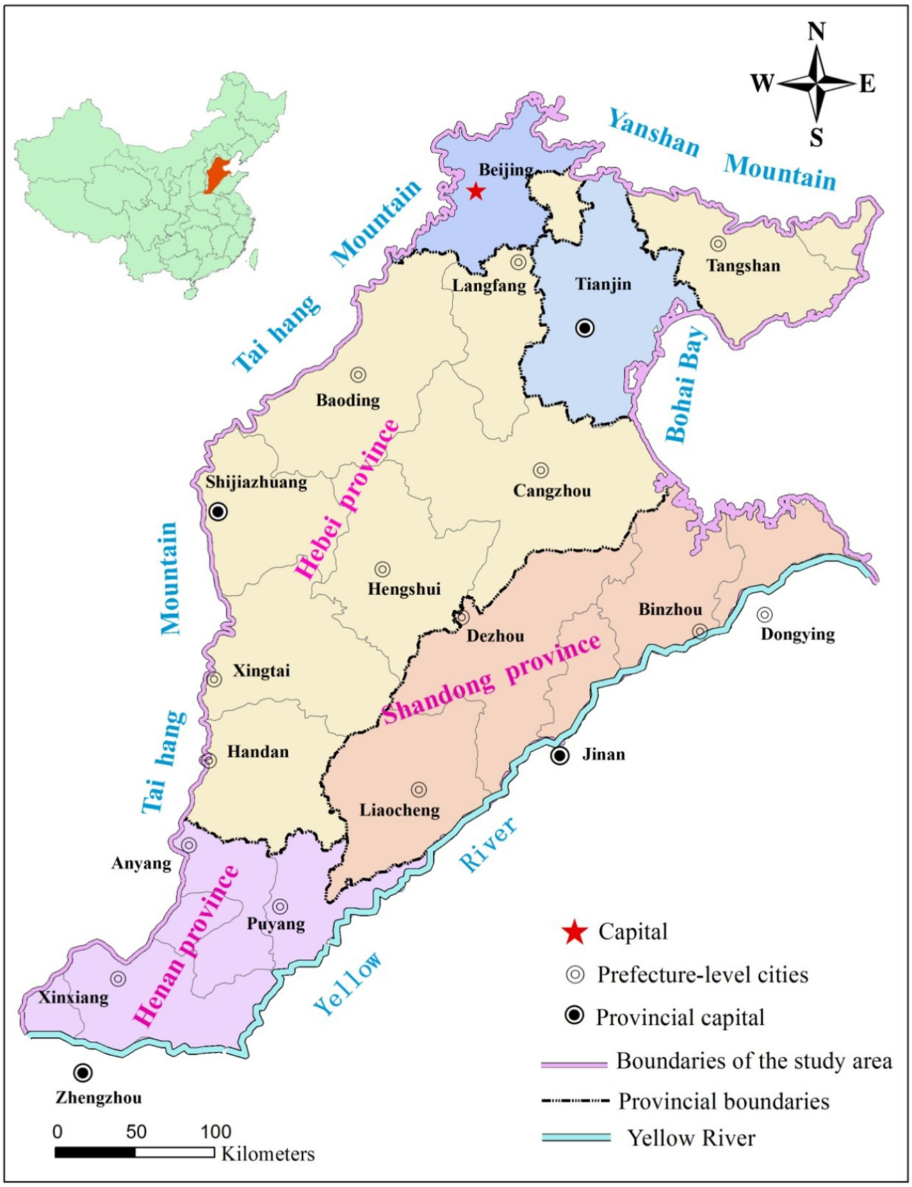


Fig. 1. Map of the study area, the North China Plain.

2.2.2. DPE_GI model structure and establishment

To analyze the spatial and temporal characteristics of energy consumption at regional scales, a distributed model of energy consumption was constructed by geographical information system (GIS) system. Due to the large scale of the NCP, regional differences exist among groundwater depth and hydrological conditions. In our study, the minimum calculation unit was at the county-level (accounting for 206 counties (Supplementary information Table 1)). The area of county-level units in the NCP was generally small, with an average area of only 661.2 km^2. County-level assessments were used because many agricultural planning activities and water management practices (e.g., planted area planning, crop yield recording, and water use permitting (Zhou and Zhang, 2011)) are conducted at the county level. The county is also an important regional administrative unit in food production systems for countries like China, India and Japan (Ma et al., 2009). Therefore, the inland water levels and cropping practices were assumed similar at the county scale, and differences existed only between county-level units. The flowchart of data processing steps is shown in Fig. 2.

Based on the hypothesis above, the model was as follows:

$$E = \frac{[60\omega W_{UI}\rho g(h+\Delta h_p)]\times 10^{-6}}{0.4}\times\frac{S}{S_{\boldsymbol{w}}}\times n \qquad (1)$$

where E is the pumping energy for groundwater irrigation, KW h; ρ is density of water, and this value was considered as 1000 kg m^{-3} in this paper; g is acceleration of gravity, m s^{-2}; W_{UI} is groundwater irrigation water, which was calculated by crop water productivity, mm; ω is the proportion of groundwater in the total irrigation water; $\Delta h_{\boldsymbol{p}}$ is the average change in depth of groundwater for every irrigation, m; h is groundwater depth, m (see detail in Supporting information Fig. 2); S is the total crop planting area, hm^2; $S_{\boldsymbol{w}}$ is the single well control area, hm^2; and n is the number of irrigation events during the growing season (Chen et al., 2018; Wang et al., 2001).

$$\begin{aligned} \Delta h_p &= \frac{W_{UI}}{n}\times\mu \\ W_{UI} &= \frac{ET_{blue}}{\eta} \end{aligned} \qquad (2)$$

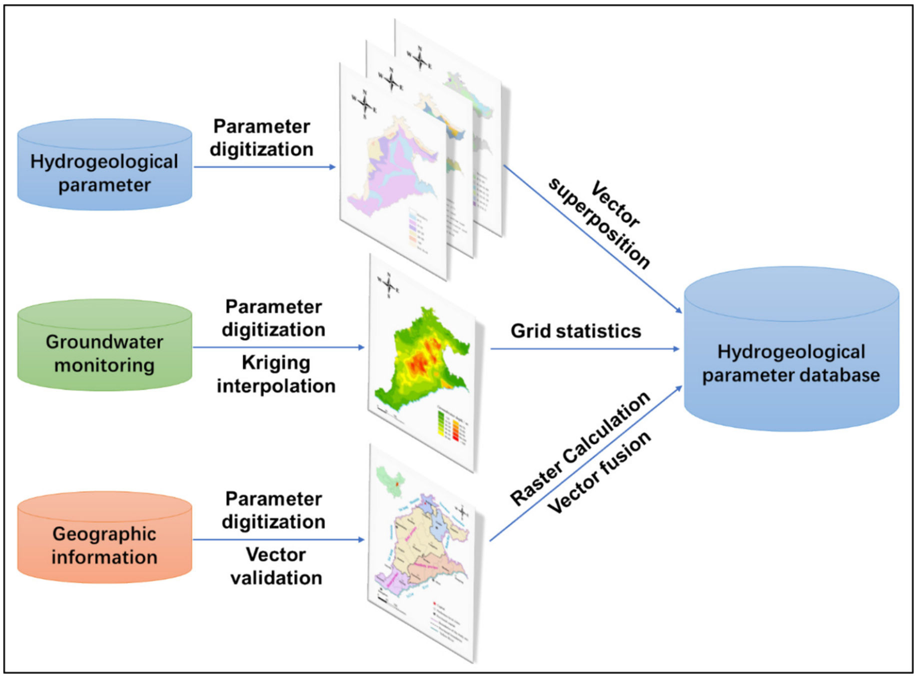


Fig. 2. Flowchart of data processing steps.

where μ denotes specific yield; η is the water efficiency of irrigation (Ma et al., 2015; Xu et al., 2018); and ET_{blue} is the blue water footprint which also means groundwater drawn from irrigation, mm.

The water consumption of crops over the entire growing season was calculated based on crop yield and a water production function. The calculation process was as follows:

$$\begin{aligned} &Y = a \cdot ET^2 + b \cdot ET + c \\ &P_{eff} = \sigma P \\ &ET_{blue} = \max(0, ET - P_{eff}) \end{aligned} \tag{3}$$

where a, b, and c denote coefficients for crop water production function (Zhang and Guo, 2016); ET is crop evapotranspiration, mm; Y is the crop yield, kg hm^{-2}; σ is the effective rainfall coefficient; P_{eff} is the effective precipitation; and P is the total precipitation. The effective utilization coefficient of precipitation was related to precipitation, rain intensity, rainfall duration, soil properties and ground cover. It was determined on the basis of actual data, as shown in Supplementary information Tables 2–3.

$$S_w = \frac{Q}{n \cdot Q_i} = \frac{3600 \cdot V \cdot U \cdot S_p \cdot (L - D)}{n \cdot Q_i} \tag{4}$$

where S_w is the area controlled by a single well, hm^2; Q is the maximum pumping capacity per single well, m^3; Q_i is the water per irrigation, m^3; V is the groundwater permeability coefficient; n is the number of irrigation events; U is the specific yield; and S_p is the pipe surface area per unit length, m; the pipe wall was assumed to be made of cement with an outside diameter of 500 mm, and the void ratio was 25%; L is the length of the well pipe, m; and D is the groundwater depth, m. The groundwater hydrogeological parameter was obtained from the China Geological Survey Bureau (see detail in Supporting information Figs. 2–4).

2.2.2.1. Parameters and distributed model construction. Based on geographic coordinates for different data sets, the attribute database of the DPE_GI model for the NCP was established, and the geographical relationship between calculation units was established digitally using spatial interpolation or superposition, which provided the basis for the calculation and analysis of energy consumption. Because the acquisition of meteorological data was not collected with enough spatial detail, kriging was used to interpolate meteorological data, transform vector data into raster data, and integrate the calculated unit data for subsequent calculation and analysis (Jeffrey et al., 2001; Pokhrel et al., 2013). The accuracy of interpolation was verified by comparing the differences of adjacent cells. According to the county boundary, the DPE_GI model database was converted to vector data by assigning attribute information to each calculating unit. Because the model attribute data and the vector data boundary and scope did not always overlap perfectly, the reconstruction and registration were used for geographic data processing. The accuracy of the established computing cells was tested by comparing the cell area with the total area, and the connectivity of point, line and polygon elements were visually inspected and adjusted to ensure continuity.

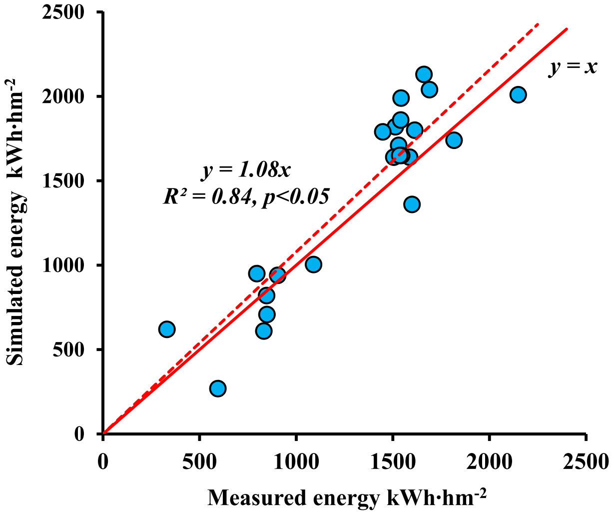


Fig. 3. Simulated versus measured energy consumption.

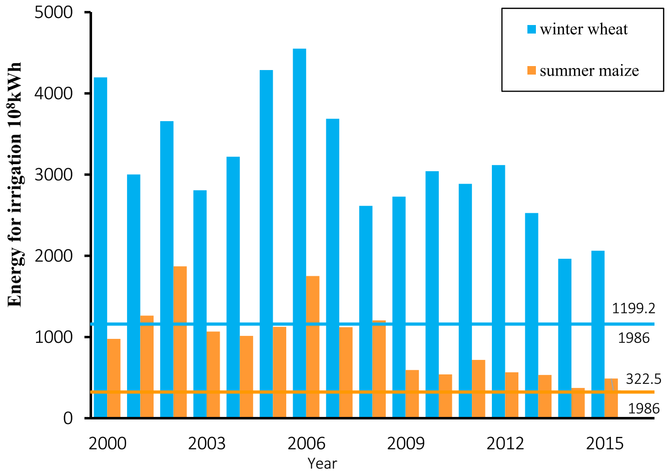


Fig. 4. The total energy consumption for irrigation in the North China Plain (2000–2015).

2.3. Data source

To build and verify the distributed energy consumption model, a database of energy consumption calculations in the NCP was established, including agricultural meteorological data, basic agricultural production data, and GIS data, etc., as follows:

(a) The average, maximum and minimum temperatures, precipitation, average relative humidity, 10 m average wind speed, sunshine duration and other long series of daily meteorological data from 69 meteorological stations in and surrounding the NCP within 50 km were collected from the China Meteorological Data Sharing Service (http://cdc.cma.gov.cn);
(b) The cultivated land, land use type and other data were obtained using a 90 × 90 m^2 digital elevation model (DEM), as well as 10 × 10 m^2 land use data and MODIS product data. The data were obtained from the Resource and Environment Data Cloud Platform (http://www.resdc.cn) and *NASA wist* (https://search.earthdata.nasa.gov);
(c) Irrigation water consumption at county level, agricultural well parameters, total output and county grain crop yield in the NCP were collected from the *Water Resources Yearbook* compiled by the *Ministry of Water Resources of China*. Groundwater depth, specific yield, and the groundwater permeability coefficient in the NCP were derived from the *Chinese geological environment groundwater level yearbook* and the *Chinese geological survey*.

2.4. Mapping and statistics

To test the statistical significance of energy consumption and driving factors over time, statistical tests were performed using the software SPSS Statistics 20 (Statistical Product and Service Solutions, IBM, USA). ArcGIS (Geographic information system, version 10.1, ESRI, Ireland) was used for spatial data analysis and mapping. Shape files were acquired for counties in the NCP, and the maps of the study area were developed in ArcGIS.

3. Results and analysis

3.1. Verification of the DPE_GI model

To verify the accuracy of the DPE_GI model, the data on electricity consumption for irrigation in 24 counties (cities) in the NCP were obtained, and a comparative analysis was made with the calculated values of this model (Li, 2009; Qian et al., 2007; Shi, 2012; Yu, 2004; Zhang, 2008). The results showed that the calculated energy consumption in this model was close to the actual value and slightly larger than the actual energy consumption (+8%), as shown in Fig. 3 ($y = 1.08x$, $R^2 = 0.84$, $P < 0.05$). In summary, the average relative error between measured and simulated energy consumption for the model was 7.8%.

In the NCP, the average area controlled by a single well is 5.48 hm^2. The spatial distribution of wells is likely related to the distribution of depth to groundwater, as shown in Supplementary information Fig. 5. In addition, the distributed model of energy consumption established in this paper can better show the differences among different regions. For example, maize production in the areas surrounding Beijing is usually non-irrigated, but irrigation is more widely used in Hengshui. Therefore, the single-well controlled area of Beijing is smaller than that in Hengshui. Qiu et al. (2018) calculated the energy consumption of groundwater extraction in the NCP. They made scientific assumptions about the ratio of groundwater to surface water and the extraction efficiency for their calculations of energy consumption. However, the internal spatial differences of groundwater level in the whole study area were not taken into account, so the spatial accuracy needs to be improved. In our paper, more detailed hydrogeological data were used to continue to estimate the water yield and control area of a single well through hydrogeological parameters, so as to obtain the energy consumption of irrigation in different areas. Therefore, the calculation results of irrigation energy consumption on county scale are more accurate in our paper. The result of the energy consumption calculation in this paper is larger (+24.2%) than that reported by Qiu et al. (2018), which may be because the groundwater levels used in this paper differed spatially and were not simply averaged, so the result of energy consumption calculation is larger than other studies (Qiu et al., 2018).

3.2. Temporal change of energy consumption in the NCP

As shown in Fig. 6, the total energy consumption for irrigation in the NCP varied substantially over time with a certain degree of fluctuation, but the overall trend of energy consumption for irrigation decreased from 2000 to 2015. To analyze the difference in energy consumption before and after over-exploitation of groundwater in NCP, 1986 was selected as the reference year (Wang et al., 2015).

Fig. 4 shows the energy consumption of winter wheat and summer maize as compared to groundwater conditions prior to over-exploitation. In 1986, the irrigation energy consumption was 119.2 × 10^8 kW h and 32.5 × 10^8 kW h, respectively. From 2000 to 2015, the energy consumption exceeded these amounts, among which the maximum irrigation energy consumption for winter wheat in 2006 was 3.8 times the 1986 value, and the minimum in 2014 was 1.6 times the 1986 value. Also, the maximum irrigation consumption in 2002 for summer maize was 5.8 times the 1986 value, and the minimum in 2014 was 1.2 times the 1986 value. The average annual energy consumption of winter wheat and summer maize was 303.1 × 10^8 and 91.2 × 10^8 kWh (2.5 times and 2.8 times the pre-exploitation value) from 2000 to 2015.

The energy consumption for irrigation of winter wheat was much higher than that of summer maize. As shown in Fig. 5, the energy consumption per unit area in the NCP has a significant decreasing trend with time ($y = 1435.8\times\text{-}0.123$, $R^2 = 0.61$; $p < 0.05$), but still much higher than the base value of 802.52 kWh·hm^{-2} in 1986. The average annual per unit area energy consumption from 2000 to 2015 was 1122.4 kW h·hm^{-2}. A significant decrease occurred between 2003 and 2013, changing from 1174.80 kWh·hm^{-2} to 965.08 kWh·hm^{-2} (−17.79%). Overall, the energy consumption per unit area decreased by about 1.7% annually.

3.3. Temporal and spatial variability of energy consumption in the NCP

The DEC_GI model was used to map the spatial distribution of energy consumption for irrigation of winter wheat and summer maize. As shown in Figs. 6, 38.57% of the planted area was higher than the

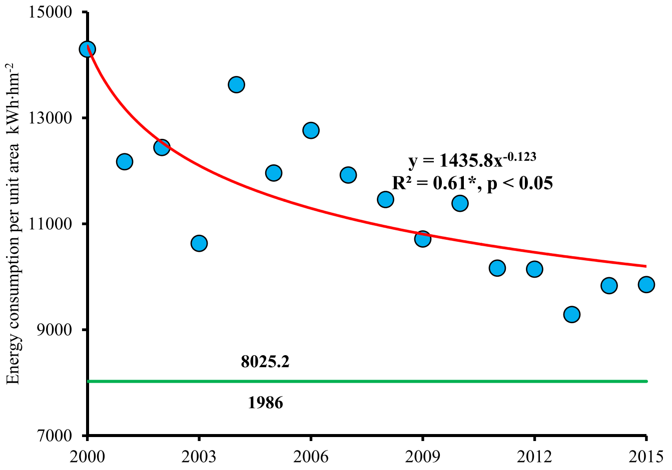


Fig. 5. Energy consumption for irrigation per unit area in the North China Plain (2000–2015).

average value. The maximum value was in Zhao County, Shijiazhuang, which reached 6670.0 kWh hm^{-2}. The minimum value was <5 times the average annual energy consumption of the NCP and was found in the area around the Bohai Sea and Tangshan. In general, higher energy consumption was found in the central and western of the NCP, especially in Hengshui and Shijiazhuang, which was consistent with the distribution of groundwater decline. The energy consumption distribution changed year by year as shown in the Supplementary information Fig. 6.

Fig. 6(a) shows that, in most of the NCP, energy consumption was low in 1986. The areas with higher energy consumption for irrigation were distributed in the northern counties and Shijiazhuang. Based on Fig. 6(b), the areas with high energy consumption have recently changed from the northern NCP to the Shijiazhuang, Hengshui, and Dezhou areas. With the exception of the Bohai Bay, the energy consumption in most areas increased by different degrees. According to Fig. 6(d), the areas with the highest energy intensity per unit area for irrigation in 2015 were also located in the Shijiazhuang and Hengshui areas, while the energy intensity per unit area for irrigation in other areas was lower than before. As shown in Fig. 6(b)–(d), the distribution of winter wheat - summer maize irrigation energy intensity did not change significantly across the region over time. Among them, the northern part of the NCP, the area around the Bohai Sea and the coast of the Yellow River consumed less energy, while the areas of Shijiazhuang, Baoding, and Hengshui in the Taihang mountains consumed more energy. The largest values of energy consumption in the NCP were all distributed in Shijiazhuang and Baoding areas for different hydrological years.

3.4. Uncertainties and sensitivity analysis

The uncertainty in the calculation of the energy consumption for groundwater pumping mainly comes from the measurement accuracy of hydrogeological and meteorological data (Muleta and Nicklow, 2005). They are directly used to calculate the energy consumption for groundwater pumping. The other part of the uncertainty is the pump efficiency, actual irrigation and the ratio of groundwater usage. This value will directly constitute the error would be directly reflected in the calculation result. Therefore, if the calculation accuracy of the energy consumption can be improved in the future, using remote sensing and other techniques for on-site measurement, etc., the result will be more reliable. In addition, the calculation of ET also depends on the accuracy of meteorological parameters.

To further investigate the impact of input parameters on the calculation of energy consumption, a sensitivity analysis was carried out to examine the effects of various main parameters on the results. The sensitivity index was used in this study to quantify how sensitive the results are to the fluctuations in parameters (Liu and Ashton, 1998):

$$S_x = \frac{\Delta x/x}{\Delta P/P} \tag{5}$$

where x is the evaluation index under original conditions, Δx is the difference of the evaluation index between original and modified conditions, P is the reference value of the parameter, ΔP is the resulting fluctuation value of the parameter variation. S_x represents the sensitivity of the parameter. By recalculating the energy consumption for groundwater pumping by increasing or decreasing the baseline value of the parameter by 10% (Marino et al., 2008), we found that the deviation of the results was small (<1.5%, Supplementary information Fig. 8).

4. Discussion

4.1. Spatial analysis of energy consumption for irrigation in the NCP

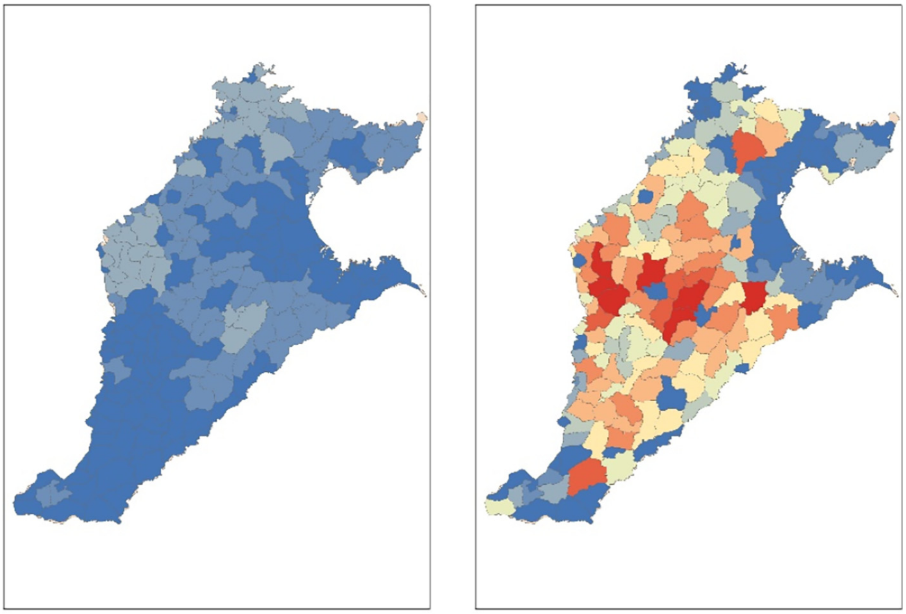
The DPE_GI model simulated energy consumption 8% higher than measured values. First, this model assumed that all water use for irrigation came from groundwater, but in many agricultural practices, farmers give priority to surface water (Liu et al., 2013). The energy required for groundwater extraction is obviously higher than that for surface water. Second, the irrigation timing during the crop growth period was set to a fixed value. However, the actual irrigating time was probably less due to costs or labor requirements (Niu et al., 2015). As for summer maize, the rainfall was relatively abundant, which can basically meet the water requirement. However, the precipitation during the period of winter wheat could not satisfy the water requirement, and a large amount of supplementary irrigation was needed. Therefore, the energy consumption of summer maize irrigation was far less than that of winter wheat.

The spatial distribution of energy consumption in a given growing season was related to the type of hydrological year. For example, in 2002, high energy consumption happened in northern Hebei, northern Henan, and northern Shandong. Since the total water demand of crops varies little from year to year, more supplementary irrigation is needed in years with less rainfall, which means dry years will lead to more irrigation and higher groundwater pumping and energy consumption.

Compared with the central and western plain areas, the energy consumption in the Bohai Bay area was relatively low, mainly because the area is not dominated by wheat cultivation. In recent decades, groundwater, as an accessible and flexible source of irrigation, has been a reliable resource to meet the food demands of the growing population (Bakker, 2012). The winter wheat - summer maize irrigation in the NCP has put great pressure on the region's energy and electricity. If the intensity of energy consumption for irrigation is maintained, the NCP will be forced toward higher costs for energy and agricultural products (Yuan and Shen, 2013). At the same time, the policy of water-saving irrigation methods and pressure-mining has been implemented in North China Plain. The average amount of irrigation water per area has decreased, the phenomenon of overexploitation of groundwater is declining, and the energy consumption of irrigation per unit area shows a downward trend.

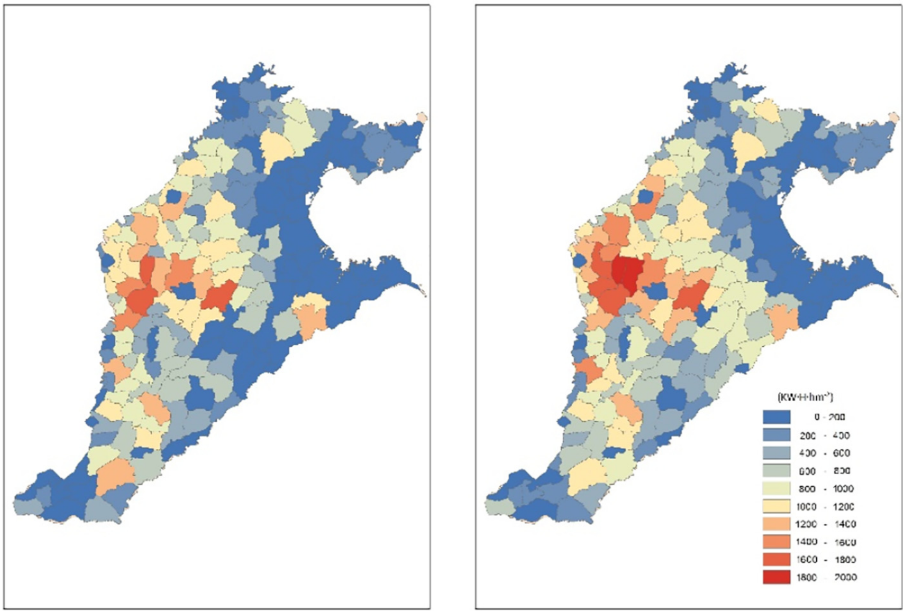
4.2. Driving factors of energy consumption for irrigation

Table 1 shows the correlation between different factors and energy consumption per unit area in 206 counties. Energy consumption per unit area was not related to population and cultivated land area, but was closely related to irrigated area, yield, precipitation, salinity and groundwater depth (Fig. 7). Based on the results, Shijiazhuang belongs to the piedmont plain of the Taihang mountain, because the pursuit of high yield leads to higher irrigation water quantity as well as higher energy consumption (Zhang et al., 2010).



(a) 1986

(b) 2001-2005



(c) 2006-2010

(d) 2011-2015

Fig. 6. Spatial distribution of energy consumption per unit area in the North China Plain.

Different precipitation in different years will lead to obvious differences in irrigation amount. With increasing precipitation in the growth period, irrigation energy consumption tends to decrease (Supplementary information Fig. 9). Because crop water demand is relatively consistent across growing seasons, the amount of precipitation directly affects the amount of supplementary irrigation required. In addition, large amounts of rainfall will supplement surface water sources in rivers, lakes, and reservoirs. Irrigated agriculture will give priority to extracting surface water, thus indirectly reducing energy consumption for groundwater pumping (Olson and Morton, 2017). Therefore, the irrigation water quantity may have some randomness, but a certain degree of correlation remains with the precipitation received in a given year. Dry years with less rainfall need more supplementary irrigation, and the more energy consumption is therefore required in dry years (Liang and van Dijk, 2016). The amount of irrigation recharge can also cause the rise of the water level of the aquifer. Studies have shown that irrigation recharge can increase the thickness of the unsaturated aquifer, especially in the area of shallow water mining in the piedmont plain, which will lead to the corresponding reduction of irrigation energy consumption (Cao et al., 2016).

Table 1
Correlation between different factors and energy consumption per unit area.

Factors	Pearson correlation coefficient	F	R-square	N
Irrigated area	0.37*	2.09	0.54	206
Yield	0.55**	2.76	0.83	206
Cultivated area	0.02	/	0.06	206
Precipitation	0.54**	2.33	0.81	206
Groundwater depth	0.51**	1.47	0.78	206
Population	0.09	/	0.12	206
Salinity	0.17	/	0.38	206

Note:
* Means $p < 0.05$.
** Means $p < 0.01$.

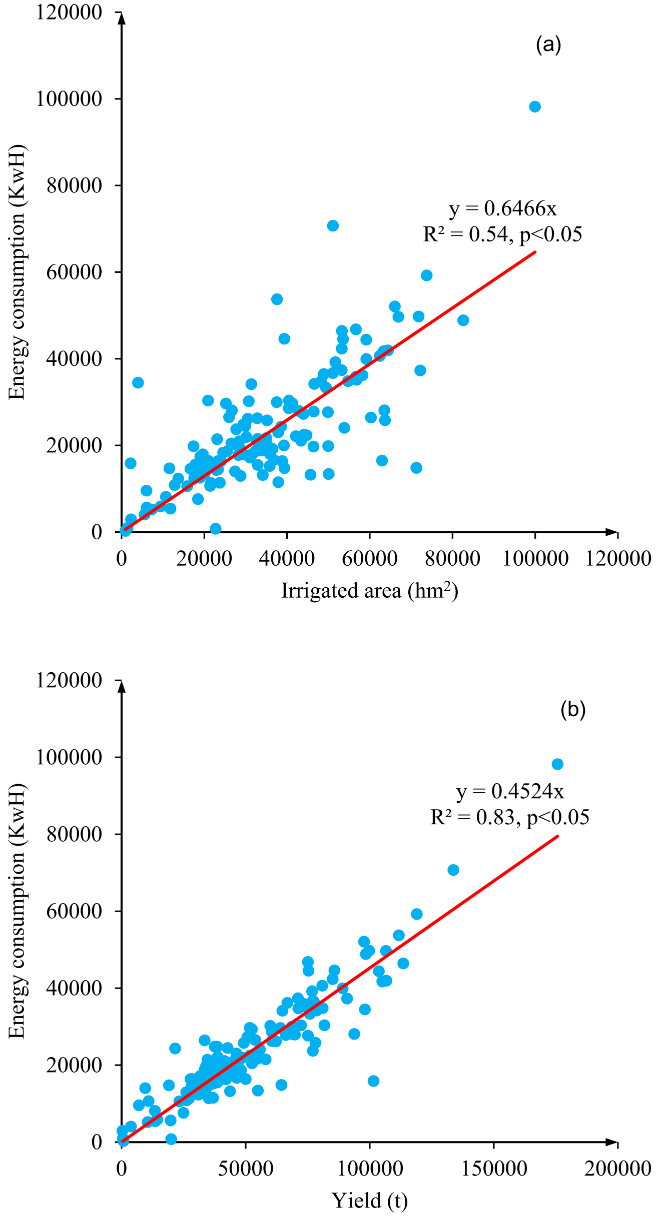


Fig. 7. The relationship between energy consumption and agricultural factors in the North China Plain: a) irrigated area and b) yield.

Groundwater over-exploitation has occurred for several years, which has made the groundwater level drop dramatically. Over this time, the cone of depression around wells in these regions has grown substantially larger. Also, the energy consumption has become larger for areas in which the groundwater level has not declined much. Groundwater-based irrigation with huge energy consumption levels have occurred in many countries around the world (Supplementary information Fig. 8). Clearly, the energy consumption in the NCP is much higher than in other regions (Ali et al., 2019; Chaudhary et al., 2009; Gul et al., 2005; Jackson et al., 2010; Miodragovic et al., 2013; Topak et al., 2009). Compared with major agricultural regions of the world, the NCP is the region with the largest energy consumption per unit area of irrigation. Surprisingly, current energy consumption for irrigation in NCP (2015) is 2.9 times of the base value in 1986, and energy consumption is much higher than other major agricultural regions of the world. The depth of groundwater has been greatly changed in NCP in the past six decades and a perennial groundwater depression cone was formed (the total area exceeded 0.03 million km^2 (Zhang et al., 2010)). It suggested that most regions' groundwater is deeper than 50 m. If the current exploitation intensity is maintained, the average depletion rate is 0.5–1.0 m y^{-1}, and the groundwater burial depth in the NCP will be deeper than 100 m in 2020 (Yang et al., 2015). This will lead to greater energy consumption in both agriculture and industry (Zhu et al., 2014).

4.3. Suggestions for reduce irrigation energy consumption

To reduce energy consumption for irrigation, water savings is needed first. Based on the existing grain production level, water-saving irrigation methods are needed, such as replacing surface irrigation with sprinkler irrigation and drip irrigation. Popularizing water-saving irrigation improves the utilization coefficient of irrigation water (Yahyaoui et al., 2017). It can effectively reduce water consumption, reduce the amount of water pumped for crop production and reduce the rate of groundwater decline, thus reducing the energy consumption due to irrigation. The government needs to regulate agricultural water withdrawals according to the intensity of energy consumption in different regions (Dillon et al., 2005; Surendran et al., 2016). On the premise of ensuring basic water consumption for agricultural production, the minimum water resources required for regional agricultural development must be determined according to the water resource carrying capacity and agricultural development goals of the NCP (Xue et al., 2017). It is also necessary to consider changing the cropping practices of the NCP and to appropriately reduce the planting density of crops (Jia et al., 2017). Planting of drought-tolerant crops should replace crops with high water consumption like winter wheat, and the rotation system should be changed to reduce the intensity of land use for agricultural production. According to the *National Technical System of Wheat Industry* and the *Chinese Academy of Agricultural Science*, etc., Chinese wheat consumption is expected to be steady but slightly increasing in the future (0.1%–0.8%). As a whole, Chinese wheat supply and demand will be basically balanced in the future, with an annual gap of 1.0 to 3.5 million tons. Therefore, wheat imports could be increased to ease the grain production demand in the NCP (Avellan et al., 2018), which will reduce wheat planting to achieve conservation measures and reduce irrigation requirements.

5. Conclusions

A distributed model of energy consumption for groundwater pumping for irrigation was established, which demonstrated the spatial distribution of energy consumption according to different climatic and agronomic conditions in the NCP. The average annual energy consumption for the winter wheat - summer maize rotation system in the NCP was 13.667 G kW h and the energy consumption per area was 1122.40 kW h·hm^{-2}. Current energy consumption for irrigation in the NCP (2015) is 2.9 times the value in 1986, and it has become the world's largest energy consumer. On a global scale, greater attention must be paid to the energy consumption associated with modern irrigation practices. Popularizing water-saving irrigation methods and adjusting cropping system practices can effectively reduce the intensity of energy consumption for irrigation.

Groundwater irrigation energy consumption is mainly related to groundwater level and irrigation water consumption. To alleviate the problem of groundwater irrigation energy consumption, we need to focus on irrigation water use. Reducing planting density and crop rotation can effectively reduce annual water consumption. Water consumption per unit area can be effectively reduced by using efficient water-saving irrigation technology or alternative water sources. The suggestions proposed in this paper are also applicable to India and other groundwater-dominated irrigation areas, which can provide effective guidance for reducing irrigation energy consumption.

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Author contributions

Y.L. and X.C. designed the research; Y.L., Z.O. and X.C. contributed data; X.C., K.T. B.Z. and Y.H. provided comments on the manuscript; X.C. analyzed the data and wrote the manuscript. All authors reviewed the manuscript.

Competing financial interests

The authors declare no competing financial interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.03.179.

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