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CALCULATION OF IRRIGATION WATER VOLUME AND EVALUATION OF WATER-SAVING BENEFITS OF FALLOW IN THE NORTH CHINA PLAIN

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Abstract
The North China Plain (NCP) is the main grain-producing region in China, and water shortage is an important factor limiting regional grain production and socioeconomic development. Since 2014, the fallow policy has been implemented in the NCP to reduce winter wheat and expand spring maize planting area. Studying the spatial and temporal distribution of regional evapotranspiration (ET), effective precipitation (PE) and effective irrigation (EI) in combination with crop types can evaluate the water saving benefits of fallow and help the rational allocation of agricultural water. In this paper, spatial calculations and analysis of ET and PE of different crops in the NCP from 2001 to 2016 were conducted based on the 500m spatial distribution rate of PML_V2 remote sensing ET products and precipitation data from meteorological stations, which led to the EI of different time scales in the NCP, and further analyzed the EI of each crop in combination with the planting areas of winter wheat, summer corn and spring corn. The average acreage of water savings under the typical fallow mode of switching from winter wheat-summer corn rotation to spring corn monoculture was compared. The results showed that with the growth of ET of the three crops and the shortage of PE makes the EI show an increasing trend, and the water saving benefit of fallow also shows an increasing trend, with a multi-year average value of 199.3 mm, which provides a scientific basis for evaluating the irrigation water saving benefit of fallow on a regional scale.
Keywords
evapotranspiration; effective precipitation; effective irrigation; fallow

1. Introduction

The NCP is the main grain producing area in China, and the grain sowing area accounts for about 80% of the total crop sowing area. For a long time, the NCP has been mainly produced under the biannual production system of winter wheat-summer corn, which makes the region one of the typical irrigation areas for agricultural production due to poor natural water resources conditions and serious uneven distribution of soil and water resources (Chen et al. 2010), irrigation water withdrawal accounts for about more than 70% of total groundwater extraction (Zhang et al. 2018), and due to the long-term over-exploitation of groundwater resources, the NCP has become the largest groundwater leakage area in the world (Shi et al. 2011; Feng et al. 2013). In order to alleviate the over-exploitation of groundwater, China started to implement the winter wheat fallow policy in 2014 to suppress the winter wheat planting area in the groundwater over-exploitation area of the NCP, before which most farmers had already actively chosen to replace the double season system of winter wheat and summer maize with a single season system of spring maize (Wang et al. 2016).

ET, also known as crop water demand, includes soil evaporation, vegetation evaporation and water surface evaporation (Zhang and Chen. 2017), and is the link between maintaining surface energy balance and land surface hydrological cycle (Zhao et al. 2020). Adequate understanding of the spatial and temporal variation of ET can help to grasp the variation pattern of crop water demand and make reasonable allocation of irrigation water resources.

Precipitation is one of the important factors affecting the growth of crops and directly affects the water balance of different crops and irrigation needs. The amount of precipitation consumed to meet the evaporation of crops is called PE, which does not include runoff, seepage to areas other than the root zone and deep seepage needed to wash out the salts.

Current research on fallow focuses on the benefits generated by social, economic and environmental aspects of fallow, with less research on the effects of water saving (Xie et al. 2018).Our study started from ET and PE, and spatially calculated and analyzed ET, PE and EI for different time periods in the NCP from 2001 to 2016, we further analyzed the EI of specific crops in combination with the planting areas of winter wheat, summer corn and spring corn and calculated the Crop Water Surplus Deficit Index (CWSDI) of each crop. The irrigation water savings under this typical fallow pattern were derived by comparing the differences in EI for winter wheat-summer corn and spring corn.

2. Materials and Methods

2.1 Study area

The North China Plain is located at 32°08′N-40°24′N，112°50′-122°40′E, with the Bohai Sea and Yellow Sea to the east, the Taihang Mountains to the west, the Yanshan Mountains to the north, and the middle and lower reaches of the Yangtze River Plain to the south, covering an area of 4×10^5 km^2 , with a temperate continental monsoon climate, abundant light and heat resources, and large and concentrated interannual variation in precipitation (Lu and Fan. 2013), the main cropping system in this area is winter wheat-summer maize biannual system. In this study, 80 meteorological stations in and around the study area were selected for precipitation data analysis and processing, and the distribution of the stations is shown in Figure 2-1.

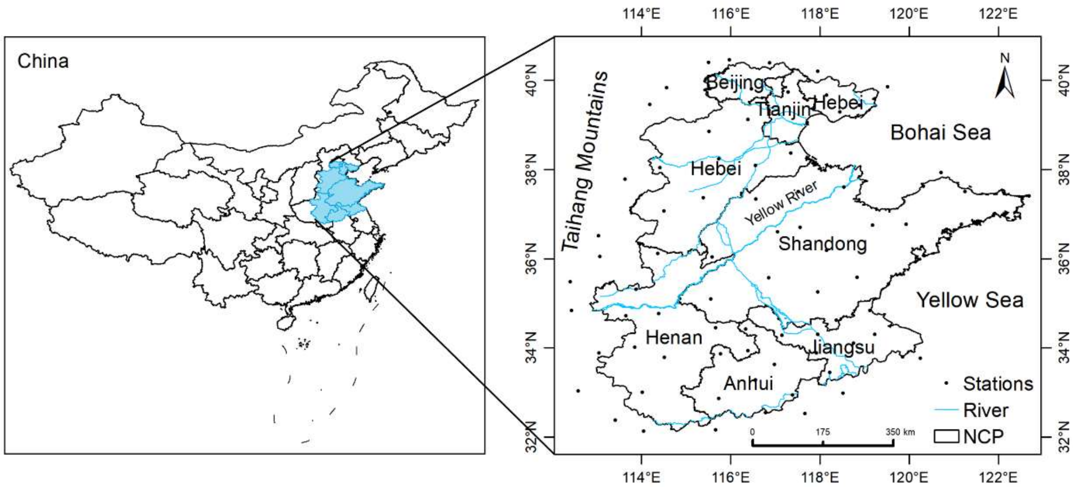

Figure 2-1 Location of the North China Plain showing meteorological stations, rivers and provincial boundaries

2.2 Data sources and processing

The meteorological data were obtained from the National Meteorological Science Data Center of China, including daily precipitation data from 80 meteorological stations in and around the NCP from 2000 to 2016; the remote sensing ET data were obtained from the global PML_V2 dataset developed by Yongqiang Zhang and his team at the Institute of Geographical Sciences and Resources, Chinese Academy of Sciences. The global PML_V2 dataset, which is a global surface ET data calculated based on the Penman-Monteith-Leuning ET model in the GEE platform with a spatial resolution of 500 m and a temporal resolution of 8 d (Zhang et al. 2019) , He et al. evaluated the applicability of three international ET products (PML_V2, MOD16A2 and SSEBop_V4) with high spatial resolution and fast update in North China, and the results showed that the ET products of PML_V2 data were closest to the observations of eddy correlator in the NCP region (He et al. 2020). The 2001-2016 land use data were obtained from the National Qinghai-Tibet Plateau Data Center, Li et al. identified the distribution of planting areas of six typical crop categories in the NCP from 2001 to 2018. The identification results were evaluated for accuracy after confusion matrix, comparison with winter wheat sowing areas from county statistical yearbooks, and comparison with Landsat extracted winter wheat share, and all performed well with high accuracy (Li et al. 2021). From this study, two types of features were obtained for each year: winter wheat-summer corn and spring corn. In this paper, three different time scales were divided into winter wheat growing season (October to June), spring corn growing season (May to August) and summer corn growing season (July to September), and the annual values were synthesized from winter wheat growing season and summer corn growing season, and monthly ET was synthesized by Google Earth Engine and accumulated according to the three different time scales.

2.3 Research Methodology

2.3.1 Calculation of EI

The soil water balance equation for irrigated farmland is as follows:

$$P + I + E = ET + R + D + \Delta W \quad (2\text{-}1)$$

Where P is precipitation, I is irrigation, E is upward recharge of groundwater, ET is ET, R is surface runoff loss, D is soil infiltration, and △W is the change in soil water content.

In general, the upward recharge of groundwater is negligible, E=0; the change in soil water storage averaged over several months is also negligible, △W=0; in addition, soil infiltration and runoff losses are related to rainfall and irrigation, and the relationship is complex, this paper uses the PE and EI after removing the two components of and R to represent the water input, and the simplified water balance equation is:

$$PE + EI = ET \quad (2\text{-}2)$$

This leads to the formula for calculating the EI:

$$EI = ET\text{-}PE \quad (2\text{-}3)$$

Where the effective precipitation PE is calculated day by day using the formula recommended by the USDA (Fabregat-Safont et al. 2021):

$$PE = \begin{cases} P(4.17 - 0.2P) & P < 8.3mm/d \\ 4.17 + 0.1P & P \geq 8.3mm/d \end{cases} \quad (2\text{-}4)$$

Then, kriging interpolation was used to derive the PE of the region at different time periods.

2.3.2 Slope trend analysis

One-dimensional linear regression models are widely used to analyze trends in observed data (Wang et al. 2019):

$$Slope = \frac{n\sum_{i=1}^{n} ix_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} x_i}{n\sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2} \quad (2\text{-}5)$$

where n is the number of observation years, and Xi is the observation value of the ith year.

2.3.3 Mann-Kendalll trend test

The Mann-Kendall nonparametric trend test is a method recommended by the World Meteorological Organization and is widely used for trends in climate and hydrological series (Burn and Elnur, 2002), and the statistic S is defined as:

$$S = \sum_{k=1}^{n-1} \sum_{i=k+1}^{n} sign(x_i - x_k) \quad (2\text{-}6)$$

$$sign(x_i - x_k) = \begin{cases} +1, (x_i - x_k) > 0 \\ 0, (x_i - x_k) = 0 \\ -1, (x_i - x_k) < 0 \end{cases} \quad (2\text{-}7)$$

The significance of the trend is determined by the Z-value obtained from the following equation:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}, S > 0 \\ 0, S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}, S < 0 \end{cases} \quad (2\text{-}8)$$

Where Z is the statistical value, Z>0 indicates an increasing trend and Z<0 indicates a decreasing trend. absolute values of Z greater than 1.645, 1.960 and 2.576 indicate passing the significance test with 90%, 95% and 99% confidence levels, respectively.

2.3.4 CWSDI calculation

The Crop Water Surplus Deficit Index (CWSDI) characterizes the degree of water surplus and deficit during crop reproduction and is calculated as follows:

$$CWSDI = \frac{PE - ET}{ET} \quad (2\text{-}9)$$

CWSDI can better characterize the degree of wetness of farmland and crop drought and flood conditions. CWSDI > 0 indicates a water surplus, CWSDI = 0 indicates a water balance, and CWSDI < 0 indicates a water deficit at that stage of fertility.

3. Results

3.1 Spatial and temporal distribution characteristics and trends of ET, PE and EI in the NCP

As can be seen from Figure 3-1, the ET in the NCP from 2001 to 2016 ranged from 577.4 to 688.7 mm, with an average of 624.4 mm, and the results of the trend analysis showed that the overall annual scale ET showed a non-significant increasing trend with a rate of 3.86 mm/year during the study period; the ET in the winter wheat season ranged from 311.5 to 374.5 mm, with an average value of 345.0mm, showing a non-significant growth trend and a rate of 0.40mm/year; the ET of summer corn season ranged from 230.2 to 314.2 mm, with an average value of 279.4 mm, showing a significant growth trend and a rate of 3.47 mm/year, the ET of spring corn season ranged from 334.4 to 415.4 mm, with an average value of 383.7 mm, showing a significant growth trend and a rate of 4.12 mm/year. The winter wheat season, summer corn season, and spring corn season accounted for 55.3%, 44.8%, and 61.5% of the annual ET, respectively.

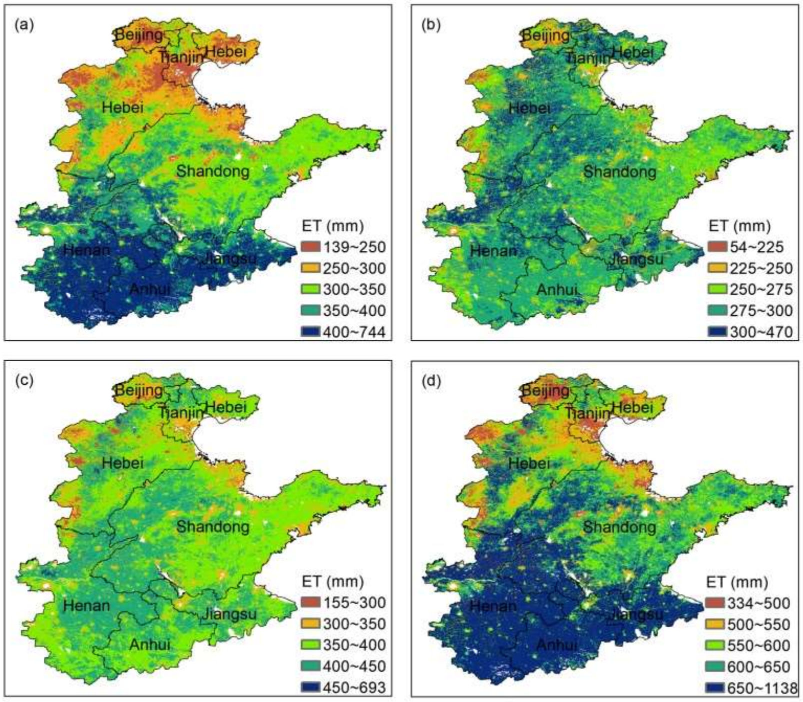

Figure 3-1 Spatial distribution of ET in the North China Plain at different time periods from 2001 to 2016 (a: winter wheat season; b: summer corn season; c: spring corn season; d: year）

The annual mean ET of the North China Plain shows a pattern of high in the south and low in the north. In the front plain of Taihang Mountains of Hebei and the southeastern part of Henan, Anhui and Shandong, where the winter wheat-summer maize rotation is concentrated, the ET is generally high, and the low value areas are mainly distributed in Bohai Bay and urban areas. The spatial distribution of winter wheat seasonal ET and annual average ET is basically the same, and the high value area of summer maize seasonal ET is mainly concentrated in the irrigation area along the Yellow River and the front plain of Taihang Mountains. Since the area planted with spring maize is smaller and has less influence on regional ET patterns, there is no significant spatial variation in ET patterns during the spring maize season, with most areas concentrated in the range of 350-450 mm.

The spatial distribution characteristics of ET at different time scales and significance tests were obtained by MK trend test, as shown in Figure 3-2. The test results of the annual average ET are: about 90.1% of the area showed an increasing trend, of which 46.6% showed a significant increase, mainly in the irrigation area along the Yellow River, 9.9% showed a decreasing trend, mainly in the front plain of Taihang Mountains, and only 1.5% showed a significant decrease. Wheat season ET was up in 54.1% of the areas, of which 9.9% showed significant growth, mainly in Henan and the front plain of Taihang Mountains, and down in 45.9% of the areas, of which only 4.2% showed significant decline, mainly in the junction of Shandong and Hebei. In summer corn season, 97.4% of the area showed an increasing trend in ET, with a significant increase of 68.4%, and the increased area occupied almost the entire NCP. The spring corn season also showed an increasing trend in ET over 97% of the area and a significant increase of 68.6%, indicating that the increasing trend in ET throughout the year was mainly contributed by the corn season.

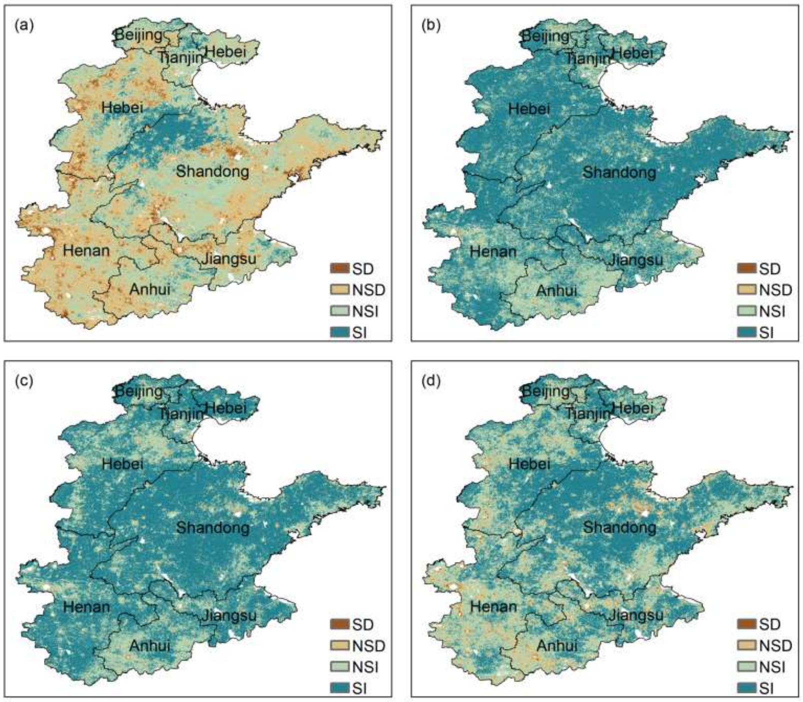

Figure 3-2 Spatial distribution of significant changes in ET in the North China Plain during different fertility periods from 2001 to 2016 (a: winter wheat season; b: summer maize season; c: spring maize season; d: year. SI: significant increase; NSI: non-significant increase; SD: significant decrease; NSD: non-significant decrease)

As can be seen from Figure 3-3, the PE in the NCP from 2001 to 2016 ranged from 206.1 to 294.5 mm, with an average of 242.8 mm, and the results of the trend analysis showed that the annual scale PE in the study period showed an overall trend of non-significant decrease with a decline rate of 1.28 mm/year; the PE in the winter wheat season ranged from 74.8 to 147.4 mm, with an average of 123.5 mm, showing a trend of non-significant decrease, with a decline rate of 0.99 mm/year. The PE in summer corn season ranged from 76.2 to 152.6 mm, with an average value of 119.3 mm, showing a trend of non-significant decrease and a decline rate of 0.29 mm/year. The PE in the spring corn season ranged from 112.3 to 170.4 mm, with an average value of 143.6 mm, showing a non-significant decreasing trend and a decreasing rate of 0.90 mm/year. The winter wheat season, summer corn season and spring corn season accounted for 50.9%, 49.1% and 59.1% of the annual PE, respectively.

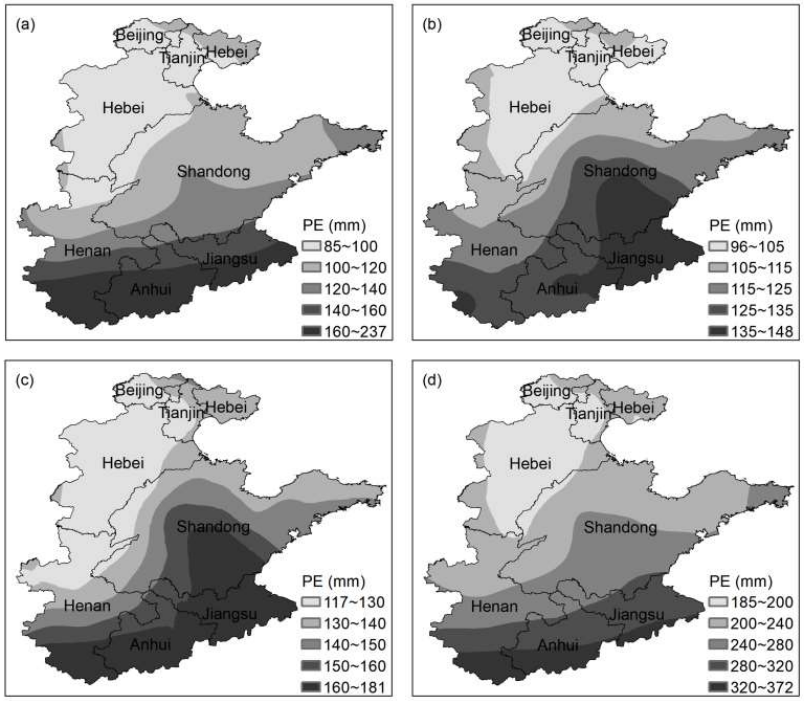

Figure 3-3 Spatial distribution of effective precipitation in the North China Plain during different fertility periods from 2001 to 2016 (a: winter wheat season; b: summer maize season; c: spring maize season; d: year)

The annual average PE in the NCP shows a decreasing trend from south to north and from east to west, and the spatial distribution pattern at different fertility scales is basically consistent with the annual average, with the high value areas distributed in a band in Henan, Anhui and Jiangsu, and the low value areas distributed in Beijing, Tianjin and around Hebei.

The MK test results show (Figure 3-4) that the PE in the vast majority of areas at different time scales shows a trend of non-significant changes, with 36.2% of the annual average PE area not significantly increasing and 62% not significantly decreasing, with the increasing area mainly located in the northern part of the NCP and the remaining areas mostly showing a decreasing trend. The rising area of winter wheat season has a wide range of shrinkage compared with the whole year, and only 14.3% of the area shows a rising trend, while the rising areas of summer corn season and spring corn season account for 33.9% and 37.7% respectively, which are basically consistent with the spatial distribution and percentage of the whole year, thus it can be seen that the rising trend of annual PE is also mainly contributed by the corn season.

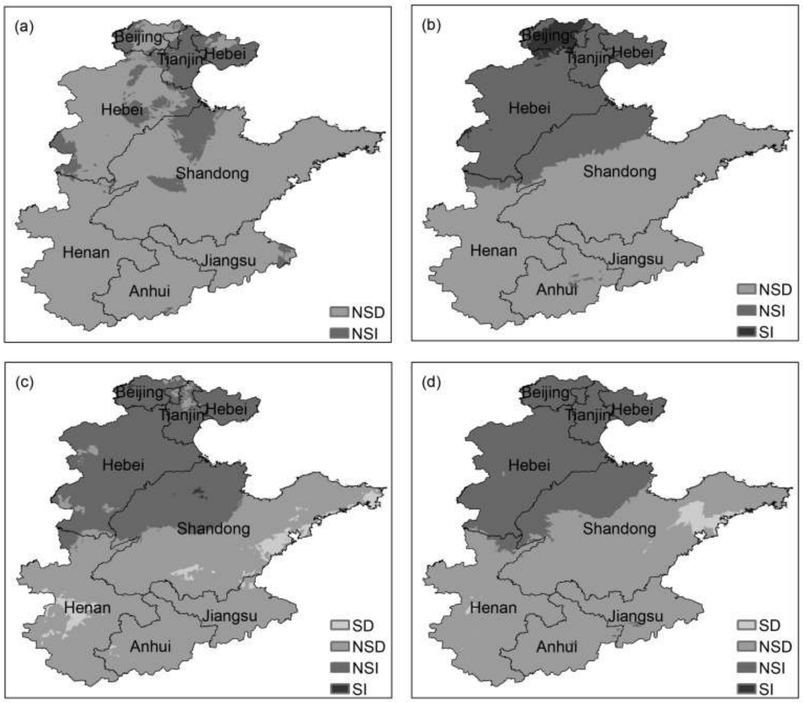

Figure 3-4 Spatial distribution of significant changes in effective precipitation in the North China Plain during different fertility periods from 2001 to 2016 (a: winter wheat season; b: summer maize season; c: spring maize season; d: year)

As can be seen from Figure 3-5, the EI in the NCP from 2001 to 2016 ranged from 283.4 to 455.7 mm, with an average of 381.7 mm, and annual scale EI showed a non-significant increasing trend with a rate of 5.13 mm/year; the EI in the winter wheat season ranged from 169.7 to 258.2 mm, with an average of 221.5 mm, with an overall non-significant growth trend and a rate of 1.39 mm/year. The EI of summer corn season ranged from 78.2 to 216.5 mm, with an average value of 160.3 mm, showing an overall non-significant growth trend and a rate of 3.74 mm/year. The EI in spring corn season ranged from 165.2 to 290.4 mm, with an average value of 240.2 mm, showing a significant growth trend and a rate of 5.02 mm/year. The winter wheat season, summer corn season, and spring corn season accounted for 58.0%, 42.0%, and 62.9% of the annual EI, respectively.

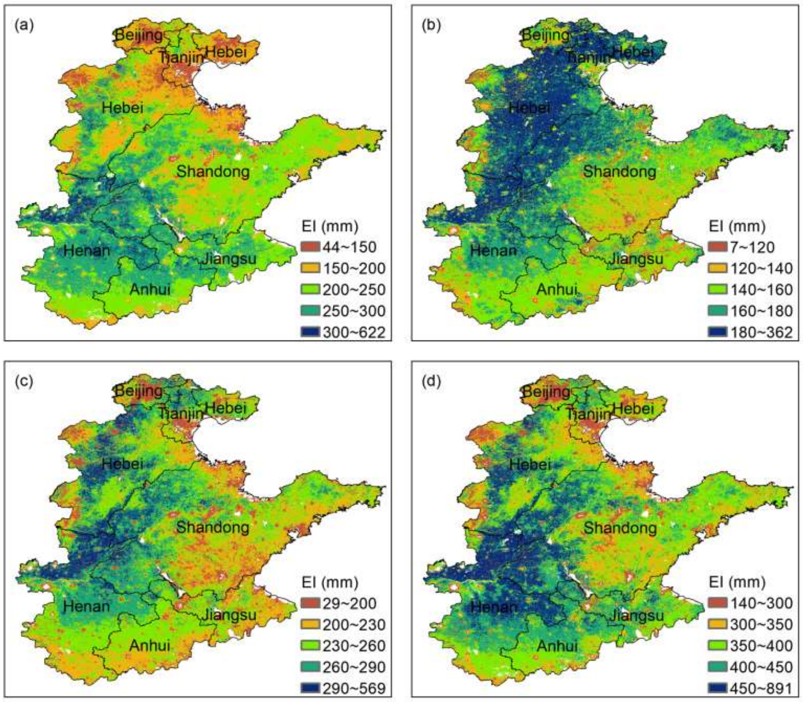

Figure 3-5 Spatial distribution of effective irrigation in the North China Plain during different fertility periods from 2001 to 2016 (a: winter wheat season; b: summer maize season; c: spring maize season; d: year)

The high value of the annual average EI in the NCP is mainly concentrated in the irrigation area along the Yellow River and the front plain of Taihang Mountains, and the low value is mainly concentrated in the coastal plain and southeastern Shandong, while the annual average EI in most other areas is 350-450 mm. The EI in the winter wheat season is consistent with the annual average distribution pattern, and the EI in the summer corn season is mainly concentrated in most areas north of the Yellow River, while the high value of the EI in the spring corn season is reduced in northern Henan compared with the annual average, and the rest is basically consistent.

The MK test results show (Figure 3-6) that 93.3% of the annual average EI shows an increasing trend, of which 34.7% shows a significant increase, the area with significant increase is mainly concentrated in Shandong Peninsula, 6.0% of the area shows a decreasing trend, mainly distributed in the front plain of Taihang Mountains, only 0.7% of the area shows a significant decreasing trend, the area showing an increase in the winter wheat season has The area that showed an increase in the winter wheat season was reduced, accounting for 70.6%, and the reduced areas were located in the southern part of the NCP and the front plain of Taihang Mountains, while the area that showed an increase in the summer and spring corn seasons both exceeded 95%, which shows that the trend of increasing EI is also contributed by the corn season.

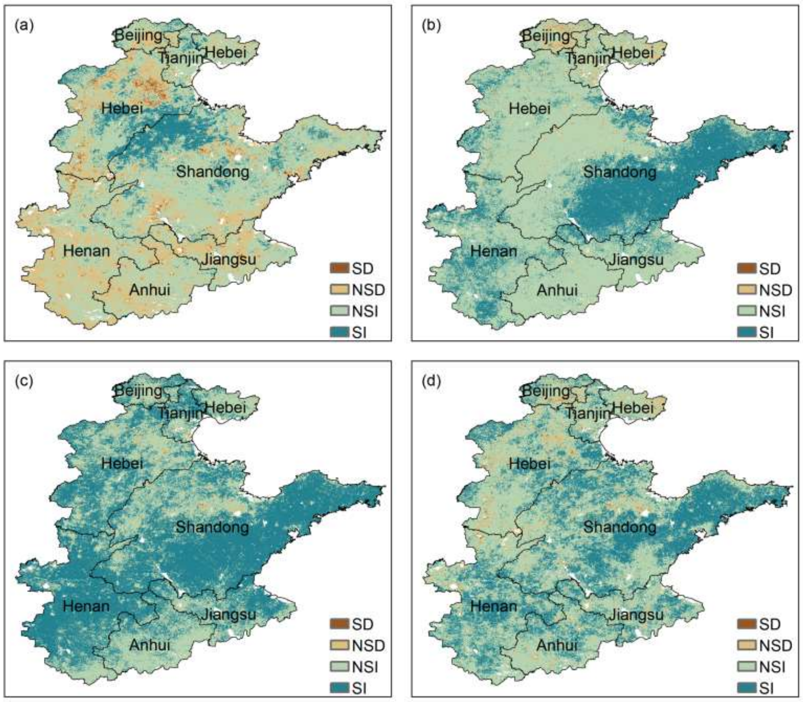

Figure 3-6 Spatial distribution of significant changes in effective irrigation in the North China Plain during different fertility periods from 2001 to 2016 (a: winter wheat season; b: summer maize season; c: spring maize season; d: year)

The box line graphs of ET, PE and EI for different time periods are shown in Figure 3-7. From the graphs, it can be seen that the fluctuation of ET is smaller in summer than in winter, while the PE is the opposite, and the fluctuation of EI is larger than that of ET and PE.

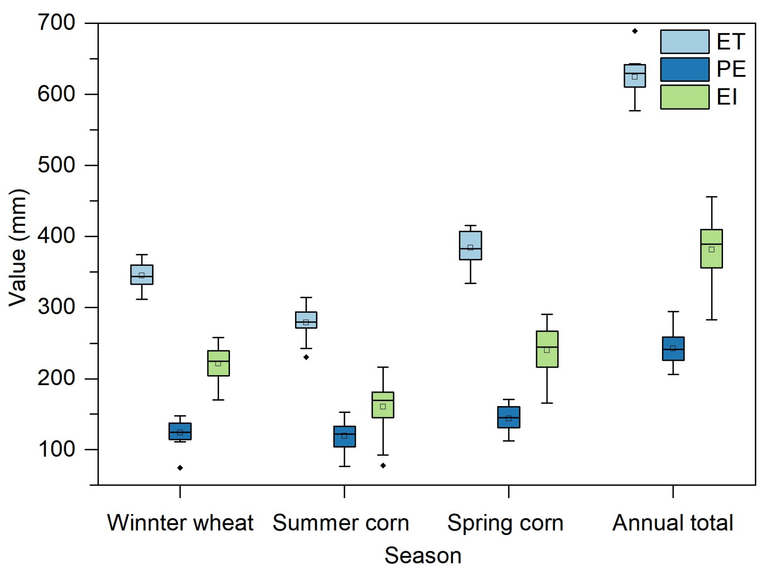

Figure 3-7 Box line plots of ET, PE, and EI for different fertility periods in North China Plain from 2001 to 2016

3.2 Trends of ET, PE and EI of three major crops and evaluation of water saving benefits of fallow

According to the land use data, two types of spring corn and winter wheat-summer corn were extracted from them, and their sown areas from 2001 to 2016 year by year are shown in Figure 3-8. As can be seen from the figure, the interannual fluctuation of the sown area of spring corn is larger, the largest area was sown in 2005, accounting for 17% of the cultivated area, while it plummeted to a nadir of 1.27% in 2006, with a multi-year average of 5.74%, and the interannual fluctuation of the sown area of winter wheat-summer corn is smaller, the largest area was sown in 2006 with 45.87% and the smallest in 2003 with 37.7%, with a multi-year average of 42.02%. The sown area of spring maize and winter wheat-summer maize complement each other, and the sum of their areas basically accounts for half of the cultivated area.

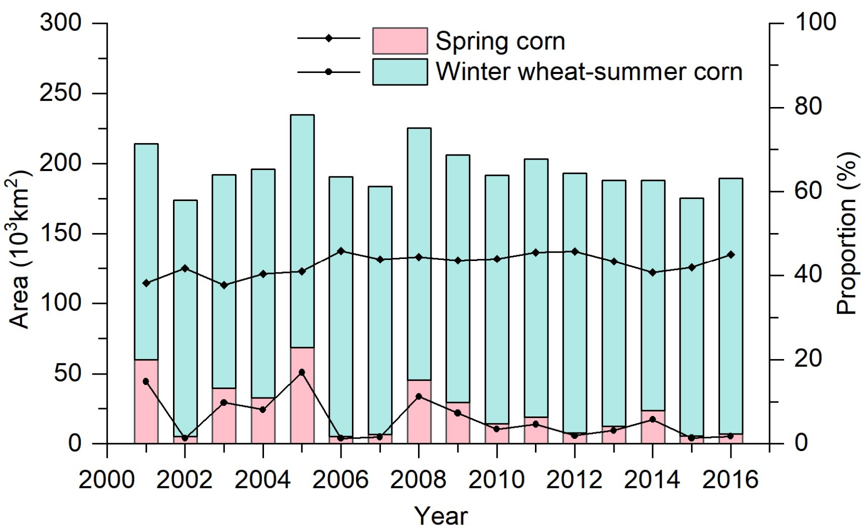

Figure 3-8 Area and proportion of spring and winter wheat-summer corn planted in the North China Plain from 2001 to 2016

The multi-year average of winter wheat ET was 388.4 mm, which increased at a non-significant rate of 0.56 mm/year, the multi-year mean ET of summer maize was 287.3 mm, which increased significantly at a rate of 3.80 mm/year, and the multi-year mean ET of spring maize was 353.2 mm, with a non-significant decrease at a rate of 2.49 mm/year. The mean value of ET of winter wheat-summer corn rotation was 675.7 mm, which increased significantly at a rate of 4.36 mm/year.

The multi-year average PE for winter wheat was 134.6 mm, with a non-significant decrease at a rate of 1.14 mm/year, the multi-year average PE for summer maize was 122.4 mm, with a non-significant decrease at a rate of 0.74 mm/year, and the multi-year average PE for spring maize was 133.9 mm, with a non-significant increase at a rate of 0.47 mm/year. The multi-year average of PE was 257.0 mm, with a non-significant decrease at the rate of -1.88 mm/year.

The multi-year average of EI for winter wheat was 253.8 mm, with a non-significant increase at a rate of 1.70 mm/year, the multi-year average of EI for summer maize was 164.9 mm, with a significant increase at a rate of 4.54 mm/year, and the multi-year average of EI for spring maize was 219.4 mm, with a non-significant increase at a rate of 2.02 mm/year. The EI of winter wheat-summer corn rotation was 418.7 mm, which increased significantly at the rate of 6.24 mm/year.

The box line graphs of ET, PE and EI for different crops are shown in Figure 3-9. From the graphs, it can be seen that the fluctuation trend of ET, PE and EI for a single crop is smaller than that for the entire NCP at the fertility stage of that crop. Comparing the ET, PE and EI of the three crops with those of the NCP in the same period, it can be seen that the changes of winter wheat and summer corn are more consistent with those of the whole region, mainly due to the large sowing range of winter wheat-summer corn, which has a greater impact on the overall distribution pattern, while the impact of spring corn on the whole is relatively small. The significance of the spring corn season and the EI of cultivated land sown with spring corn in the NCP levels were not consistent, and even the PE within the spring corn cropland and the whole NCP had opposite trends.

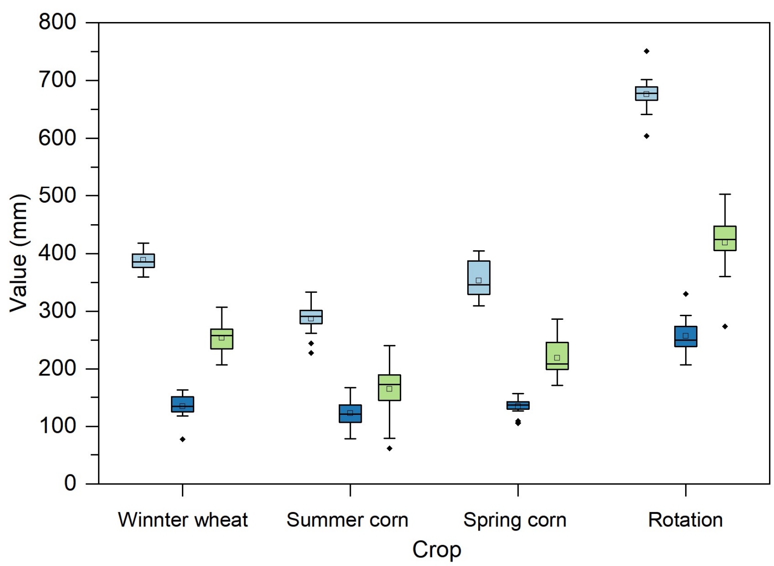

Figure 3-9 Box line plots of ET, PE and EI for different crops in North China Plain from 2001 to 2016

The CWSDI is the main index to reflect the moisture content of farmland and the state of water deficit and water saturation of crops. The results showed that the average CWSDI of winter wheat, summer corn and spring corn were -65.3%, -56.5% and -61.9%, respectively (Figure 3-10), where winter wheat decreased at a rate of 0.4%/year, summer corn decreased at a rate of 0.9%/year and spring corn decreased at a rate of 0.1%/year, and the average annual CWSDI of winter wheat-summer corn rotation was -61.8%, decreasing at a rate of 0.5%/year and they all have non-significant downward trends. Overall, the PE during the reproductive period of all three crops was severely deficient and the dependence on irrigation was high for all three crops, with summer corn being slightly less dependent on irrigation, followed by summer corn, and winter wheat being the highest. The winter wheat-summer corn rotation being longer than spring corn, along with a higher dependence on irrigation water, all of which resulted in more water consumption.

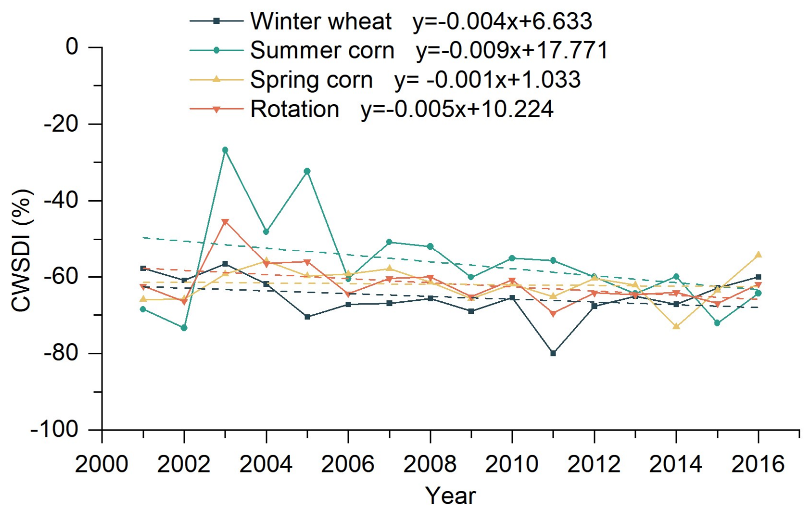

Figure 3-10 Trends of Crop Water Surplus Deficit Index for different crops from 2001 to 2016

The EI of winter wheat-summer corn was subtracted from the EI of spring corn to obtain the irrigation water saving benefit of switching from double cropping of winter wheat-summer corn to single cropping of spring corn, as shown in Figure 3-11, from which it can be seen that the irrigation water saving of fallow shows a trend of non-significant growth, and the multi-year average of saving is 199.3 mm, which is close to the field survey data of 261 mm of water that can be achieved by fallowing, as presented in the "Monitoring and Evaluation Report on the Quality of Farmland in the Seasonal Fallow Pilot Areas of Hebei Province 2017-2019" released by the Hebei Farmland Quality Monitoring and Protection Center, indicating that it is feasible to evaluate the irrigation water saving benefits of fallow on a regional scale and providing a scientific basis for the sustainable implementation of the fallow system.

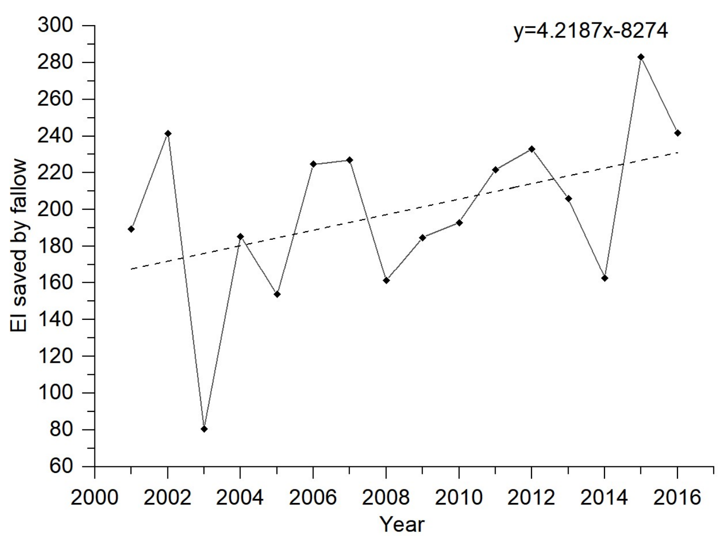

Figure 3-11 Trends in differences in effective irrigation for spring and winter wheat-summer corn from 2001 to 2016

4. Discussion

4.1. Spatial and temporal distribution patterns and causes of ET, PE and EI in the NCP

There is obvious spatial heterogeneity in the distribution pattern and trend changes of ET in the NCP. The ET of urban land is basically below 500 mm, which is mainly due to the impermeable layer underneath the towns, poor water storage capacity and weak transpiration, resulting in low ET. The low value of ET in Bohai Bay is due to the fact that the region is full of saline land and less agricultural production. The ET is increasing due to the greening of cities such as Beijing and Tianjin, the saline land in the coastal plain is transformed into arable land after treatment, and the winter wheat-summer corn growing area is expanding, while Shandong is the main vegetable growing area, and with the development of vegetable industry, more water is needed to meet the irrigation demand, so the ET in this area shows a significant increasing trend.

The PE in the NCP showed a decreasing trend from southeast to northwest, and the PE in Beijing, Tianjin and Hebei showed low values at all times, while the trend of annual PE was reversed, showing an increase in the north and a decrease in the south, and the range of the increasing trend in the spring and summer corn seasons was further expanded, indicating to some extent that the increase of annual PE occurred mainly in summer.

The EI in the NCP showed high values in the irrigation areas along the Yellow River and the front plain of Taihang Mountains in Hebei, reflecting the result of diversion irrigation, which mainly relies on the exploitation of groundwater for irrigation, which is the main cause of groundwater leakage in North China. In the northern part of the NCP, irrigation water is at high values in all time periods due to relatively low precipitation, especially in the spring and summer corn seasons, where the irrigation water is significantly higher north of the Yellow River than south of the Yellow River. In terms of the change trend, the annual is mainly increasing, and the decreasing area is mainly concentrated in the front plain of Taihang Mountains in Hebei, while the decreasing area is further expanded from the winter wheat season, reflecting to a certain extent the effectiveness of groundwater over-extraction management in the leakage area of North China.

4.2. Evaluation of water saving benefits of fallow

A large number of studies have been conducted on crop water use in the North China Plain. Liu et al. (Liu et al. 2002) used data from a large scale weighing percolator to show that the average annual irrigation volume for the wheat-corn rotation in the front plain of Taihang Mountains from 1995 to 2000 was 495 mm, and Zhang et al. (Zhang et al. 2006) observed in a long-term wheat-corn rotation from 1997 to 2005 that the irrigation volume was 434 mm and 238 mm under full and deficit irrigation, respectively. Sun et al. (Sun et al. 2010) used meteorological data and crop coefficients collected in the field from Luancheng station from 1984 to 2005 to calculate the irrigation water requirement for a normal year of wheat-corn rotation to be about 479 mm. yang et al. (yang et al. 2010) used the DSSAT and COTTON2K crop models to calculate the irrigation water requirement of 458 mm for winter wheat-summer maize rotation in North China from 1986

to 2006 on a regional scale, and these studies are close to the irrigation water requirement of 419 mm for winter wheat-summer maize rotation calculated in this study.
Among the three major crops in the NCP, winter wheat has the highest irrigation demand due to its higher crop water demand and less precipitation. In contrast, maize consumes less irrigation water than winter wheat because it receives more precipitation during its growing season (Li et al. 2005; Sun et al. 2011). Comparing the EI of winter wheat-summer maize with that of spring maize, it can be seen that the multi-year average of irrigation water saved by fallow is 199.3 mm, which is near to the survey results, and this supports the evaluation of water saving benefits of fallow at the regional scale.

5. Conclusion

This study explored the spatial and temporal distribution characteristics and trends of ET, PE and EI at different time scales across the NCP from 2001 to 2016 based on the high-precision ET product PML_V2, and further analyzed the trends of ET, PE and EI with three major crops, evaluated the dependence of different crops on irrigation by calculating the water gain/loss index, compared the differences in EI between winter wheat-summer maize rotation and spring maize monoculture, and thus evaluated the water saving benefits from fallow, with the following main conclusions:
(1) The average annual ET in the NCP is 624.4 mm, showing an upward trend, the average annual PE is 242.8 mm, showing a downward trend, and the average annual EI is 381.7 mm, showing an upward trend, and all three elements have obvious seasonal differences and are shown as spring maize season > winter wheat season > summer maize season. On the spatial scale, both ET and PE show a pattern of high in the south and low in the north, the high value area of EI is mainly concentrated in the irrigation area along the Yellow River.
(2) Further combined with crop types, ET all showed an increasing trend for winter wheat (388.4mm) > spring corn (353.2) > summer corn (287.3mm). PE showed that winter wheat (134.6 mm) > spring maize (133.9) > summer maize (122.4 mm), except for spring maize which showed an increasing trend while others showed a decreasing trend. EI all showed an increasing trend for winter wheat (253.8 mm) > spring corn (219.4 mm) > summer corn (164.9 mm).
(3) The CWSDI of winter wheat, summer corn, spring corn and winter wheat-summer corn rotation were -65.3%、-56.5%、-61.9 and -61.8%, respectively, and the CWSDI of all three crops showed a decreasing trend.
(4) EI savings from winter wheat-summer corn rotation to spring corn monoculture showed an increasing trend and a multi-year average of 199.3 mm.

References

1. Burn D.H., Elnur M.A.H., 2002. Detection of hydrologic trends and variability. Journal of Hydrology 255: 107–122. DOI: 10.1016/S0022-1694(01)00514-5
2. Chen C., Wang E.L., Yu Q., 2010. Modelling the effects of climate variability and water management on crop water productivity and water balance in the North China Plain. Agricultural

Water Management 97 (8): 1175–1184. https://doi.org/10.1016/j.agwat.2008.11.012
3. Fabregat-Safont D., Pitarch E., Bijlsma L., Matei L., Hernández F., 2021. Rapid and sensitive analytical method for the determination of amoxicillin and related compounds in water meeting the requirements of the European union watch list. Journal of Chromatography A 1658: 462605.
4. Feng W., Zhong M., Lemoine J-M., Biancale R., Hsu H-T., Xia J., 2013. Evaluation of groundwater depletion in North China using the Gravity Recovery and Climate Experiment (GRACE) data and ground-based measurements, Water Resources Research 49(4): 2110–2118. https://doi.org/10.1002/wrcr.20192
5. He S.Y., Tian J., Zhang Y.Q., 2020. Verification and comparison of three high-resolution surface ET products in North China. Resources Science 42(10): 2035-2046. https://doi.org/10.18402/resci.2020.10.19
6. Li J., Inanaga S., Li Z.H., Eneji A.E., 2005. Optimizing irrigation scheduling for winter wheat in the North China Plain. Agricultural Water Management 76(1): 8–23. https://doi.org/10.1016/j.agwat.2005.01.006
7. Li J.D., Lei H.M., 2021. Tracking the spatio-temporal change of planting area of winter wheat-summer maize cropping system in the North China Plain during 2001-2018. Computers and electronics in Agriculture 187: 106222. https://doi.org/10.1016/j.compag.2021.106222
8. Liu C.M., Zhang X.Y., Zhang Y.Q., 2002. Determination of daily evaporation and ET of winter wheat and maize by large-scale weighing lysimeter and micro-lysimeter. Agricultural and Forest Meteorology 111 (2): 109–120. https://doi.org/10.1016/S0168-1923(02)00015-1
9. Lu C.H., Fan L., 2013. Winter wheat yield potentials and yield gaps in the North China
10. Plain. Field Crops Research 143: 98–105. https://doi.org/10.1016/j.fcr.2012.09.015
11. Shi J.S., Wang Z., Zhang Z.J., Fei Y.H., Li Y.S., Zhang F.E., Chen J.S., Qian Y., 2011. Assessment of deep groundwater over-exploitation in the North China Plain. Geoscience Frontiers 2(4): 593–598. https://doi.org/10.1016/j.gsf.2011.07.002
12. Sun Q.P., Kröbel R., Müller T., Römheld V., Cui Z.L., Zhang F.S., Chen X.P., 2011. Optimization of yield and water-use of different cropping systems for sustainable groundwater use in North China Plain. Agricultural Water Management 98(5): 808–814. https://doi.org/10.1016/j.agwat.2010.12.007
13. Sun H.Y., Shen Y.J., Yu Q., Flerchinger G.N., Zhang Y.Q., Liu C.M., Zhang X.Y., 2010. Effect of precipitation change on water balance and WUE of the winter wheat–summer maize rotation in the North China Plain. Agricultural Water Management 97: 1139–1145. https://doi.org/10.1016/j.agwat.2009.06.004
14. Wang H., Ji G.X., Xia J.S., 2019. Analysis of Regional Differences in Energy-Related PM2.5 Emissions in China: Influencing Factors and Mitigation Countermeasures. Sustainability 11(5): 1409. https://doi.org/10.3390/su11051409
15. Wang, X., Li, X.B., Xin, L.J. Tan M.H., Li S.F., Wang R.J., 2016. Ecological compensation for winter wheat abandonment in groundwater over-exploited areas in the North China Plain. Journal of Geographical Sciences 26: 1463–1476. https://doi.org/10.1007/s11442-016-1338-4.

16. Xie, H.L., Cheng, L.J., Lu, H., 2018. “Farmers’ responses to the winter wheat fallow policy in the groundwater funnel area of China.” Land Use Policy 73: 195–204. https://doi.org/10.1016/j.landusepol.2018.02.003

17. Yang Y.M., Yang Y.H., Mowiwo J.P., Hu Y.K., 2010, Estimation of irrigation requirement for sustainable water resources reallocation in North China, Agricultural Water Management 97(11): 1711–1721. https://doi.org/10.1016/j.agwat.2010.06.002

18. Zhang T., Chen Y.B., 2017. “Analysis of dynamic spatiotemporal changes in actual ET and its associated factors in the pearl river basin based on MOD16.” Water 9(11): 832. https://doi.org/10.3390/w9110832

19. Zhang Y.C., Lei H.M., Zhao W.G., Shen Y.J., Xiao D.P., 2018. Comparison of the water budget for the typical cropland and pear orchard ecosystems in the North China Plain. Agricultural Water Management 198: 53−64. https://doi.org/10.1016/j.agwat.2017.12.027

20. Zhang Y.Q., Kong D.D., Gan R., Chiew F H.S., McVicar T.R., Zhang Q., Yang Y.T., 2019. Coupled estimation of 500 m and 8-day resolution global ET and gross primary production in 2002—2017. Remote Sensing of Environment 222: 165-182. https://doi.org/10.1016/j.rse.2018.12.031

21. Zhang X.Y., Pei D., Chen S.Y., Sun H.Y., Yang Y.H., 2006. Performance of double cropped winter wheat–summer maize under minimum irrigation in the North China Plain. Agronomy Journal 98: 1620–1626. https://doi.org/10.2134/agronj2005.0358

22. Zhao J.F, Li C., Yang T.Y., Tang Y.H., Yin Y.L. Luan X.B. Sun S.K., 2020. “Estimation of high spatiotemporal resolution actual ET by combining the SWH model with the METRIC model.” Journal of Hydrology, 586: 124883. https://doi.org/10.1016/j.jhydrol.2020.124883