agriculture

Article

Optimal Irrigation under the Constraint of Water Resources for Winter Wheat in the North China Plain

Xiaoli Shi [1,2,3,*], Wenjiao Shi [2,4,*], Na Dai [1,5] and Minglei Wang [2,4]

1 Hebei Key Laboratory of Environmental Change and Ecological Construction, School of Geographical Sciences, Hebei Normal University, Shijiazhuang 050024, China
2 Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
3 Hebei Technology Innovation Center for Remote Sensing Identification of Environmental Change, Geocomputation and Planning Center, Hebei Normal University, Shijiazhuang 050024, China
4 College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China
5 Bayannaoer City No. 1 Middle School, Bayannaoer 015000, China
* Correspondence: shixl@mail.hebtu.edu.cn (X.S.); shiwj@lreis.ac.cn (W.S.)

Abstract: The North China Plain (NCP) has the largest groundwater depletion in the world, and it is also the major production area of winter wheat in China. For sustainable food production and sustainable use of irrigated groundwater, it is necessary to optimize the irrigation amount for winter wheat in the NCP. Previous studies on the optimal irrigation amount have less consideration of the groundwater constraint, which may result in the theoretical amount of optimal-irrigation exceeding the amount of regional irrigation availability. Based on the meteorological data, soil data, crop variety data, and field management data from field experimental stations of Tangshan, Huanghua, Luancheng, Huimin, Nangong, Ganyu, Shangqiu, Zhumadian and Shouxian, we simulated the variation of yield and water use efficiency (WUE) under different irrigation levels by using the CERES-Wheat model, and investigated the optimal irrigation amount for high yield (OI_y), water saving (OI_{WUE}), and the trade-off between high yield and water saving (OI_t) of winter wheat in the NCP. Based on the water balance theory, we then calculated the irrigation availability, which was taken as the constraint to explore the optimal irrigation amount for winter wheat in the NCP. The results indicated that the OI_y ranged from 80 mm to 240 mm, and the OI_{WUE} was 17% to 67% less than OI_y, ranging from 0 mm to 200 mm. The OI_t was between 80 mm and 240 mm, realizing the co-benefits of high yield and water saving. Finally, we determined the optimal irrigation amount (62–240 mm) by the constraint of irrigation availability. Our results can provide a realistic and scientific reference for the security of both grain production and groundwater use in the NCP.

Keywords: optimal irrigation; sustainable irrigation; yield; water use efficiency; North China Plain

Citation: Shi, X.; Shi, W.; Dai, N.; Wang, M. Optimal Irrigation under the Constraint of Water Resources for Winter Wheat in the North China Plain. *Agriculture* **2022**, *12*, 2057. https://doi.org/10.3390/agriculture12122057

Academic Editor: David Maxwell Freebairn

Received: 4 November 2022
Accepted: 28 November 2022
Published: 30 November 2022

1. Introduction

As one of the major production areas, the North China Plain (NCP) produces 60–80% of the winter wheat in China [1]. For precipitation only meets 30–45% of the water requirement of winter wheat during the growing season, the increased yield has largely relied on unsustainable overuse of water resources in the NCP, especially groundwater [2]. Local farmers irrigate the winter wheat several times, resulting in the largest groundwater depletion in the world. Consequently, a series of eco-environmental problems occurred, such as land surface subsidence, seawater intrusion, streamflow depletion, wetlands, and ecological damages, which seriously affected the material basis of food production in the NCP [3]. Therefore, for sustainable food production and to relieve the pressure of groundwater exploitation, it is necessary to optimize the irrigation amount for winter wheat in the NCP.

The main indicators of optimal irrigation amount are currently yield and water use efficiency (WUE). High yield is the direct objective of agricultural production and the most used indicator when evaluating the optimal irrigation amount. For example, Boumaza et al. [4] studied the optimal irrigation according to the maximum biomass production. Some studies applied the yield as the only indicator to assess the optimal irrigation amount, without considering the water utilization during crop growth, which caused high water consumption with high yield. Thus, some scholars combined yield and WUE to explore the optimal irrigation amount of crops. For example, based on the yield and WUE changes with irrigation, some researchers investigated the optimal irrigation amount for winter wheat in the Guanzhong Plain and the NCP respectively [5]. Compared with yield, the relationship between input water and output yield is considered in the WUE, which emphasizes the productivity of water resources, so the WUE is recommended as a common index to characterize water saving. However, most of the previous studies determined the optimal irrigation amount based on the variation patterns of yield and WUE with different irrigation levels, lacking a comparison with the water availability. Thus, the recommended optimal irrigation amount may be unsustainable if it exceeds the irrigation availability. In general, in addition to yield and WUE, the optimal irrigation amount should also focus on the water balance and the natural carrying capacity of the available water to truly realize water saving and sustainable food production.

Field experiments and model simulations are the main methods to investigate the optimal irrigation amount for crops. For example, based on a 16-year field experiment using seven irrigation schedules in the winter wheat-summer maize double cropping system, the optimal irrigation was determined in the Luancheng station of the NCP [6]. Field experiments can accurately evaluate the optimal irrigation; However, it is difficult to apply on a large spatial and temporal scale because of the differences in climate and soil conditions among regions [7]. In recent years, an increasing number of models have been employed in the evaluation of irrigation optimization [5,8]. The crop model can simulate the growth process of crops by setting different environmental parameters, which is a useful complement to the traditional field experiment and has good performance in regional applications [9]. Nevertheless, most of the current studies still simulated the relationship between indicators (yield, WUE) and irrigation level, lacking comparison with available irrigation water. In fact, the determination of optimal irrigation amount needs to account for both simulation results and constraints of water availability.

The objectives of the present analysis are: (1) to explore the optimal irrigation amount for high yield, water saving, and the trade-off between high yield and water saving of winter wheat in the NCP. (2) To calculate the irrigation availability in the NCP based on the water balance theory, and take it as the constraint to investigate the optimal irrigation amount for winter wheat in the NCP.

2. Materials and Methods

2.1. Study Area

The NCP is located in the east of China (114°–121° E, 32°–40° N), with a total area of 30×10^6 ha. It covers the Beijing, Tianjin Municipalities, Shandong Province, most of Hebei and Henan Province, and northern Anhui and Jiangsu Province (Figure 1). Prevailing soils in NCP are formed of fluvial materials from the Yellow River, which is fertile and favorable for cultivation. The climate of the NCP is temperate and monsoonal, with rainy hot summers and dry cold winters. The average annual temperature varies from 14 °C to 15 °C, and the average annual precipitation decreases from the southwest to the northeast, varying from 500 mm to 900 mm. In addition, 70% of the precipitation is concentered in the growing season of maize, while only 30% of the precipitation is in the growing season of winter wheat [10]. Water resources are merely 456 m^3 yr^{-1} per capita in NCP, which is below 1/7 of the national average and 1/24 of the world average [11]. As one of the most important agricultural areas of China, grain production, especially winter wheat, heavily relies on groundwater irrigation. With the continuous exploitation, the groundwater is experiencing rapid depletion, with a rate of 1.66–2.76 cm yr^{-1} during 2003–2020 in the NCP [12], a series of shallow groundwater depletion were formed in the pre-mountain plains, and relatively independent deep groundwater depletion appeared in the central-coastal plains. In this study, we chose nine representative experimental stations (Tangshan, Huanghua, Luancheng, Huimin, Nangong, Ganyu, Shangqiu, Zhumadian and Shouxian) from the NCP to explore the optimal irrigation.

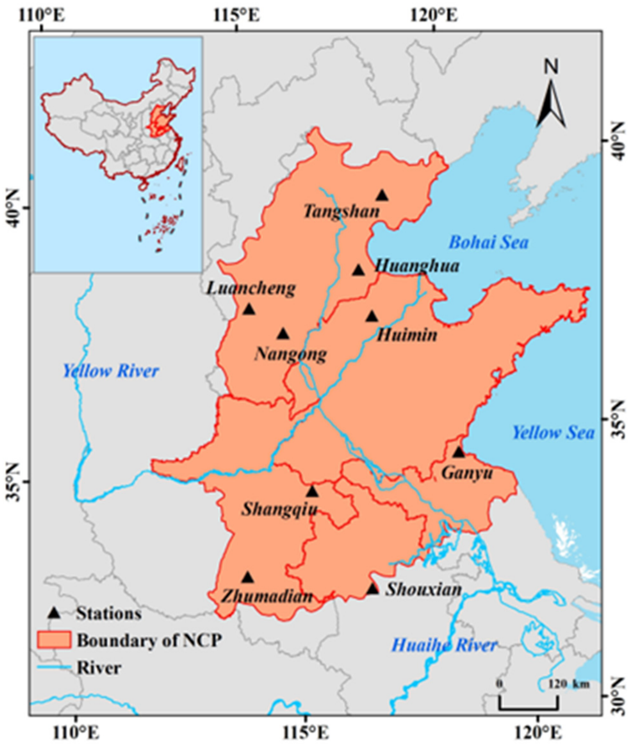

Figure 1. Location of the North China Plain.

2.2. Data

Meteorological data were obtained from the Chinese Meteorological Data Network (http://data.cma.cn/ accessed on 1 May 2020), including daily maximum temperature, daily minimum temperature, precipitation and sunlight hours from 1981 to 2017 (Figure 1). Based on the empirical formula developed by Angstrom [13], daily solar radiation was estimated by sunlight hours.

Soil data were obtained from the Chinese Soil Science Database (http://vdb3.soil.csdb.cn/ accessed on 1 May 2020), including soil type, color, soil depth, organic carbon content, soil texture, total nitrogen content, bulk density, and pH (Table 1), where organic carbon content was obtained by multiplying soil organic matter by a conversion factor of 0.58 [14].

Table 1. Soil parameters in the North China Plain.

Soil Parameters	Range
Bulk density (g cm^{-3})	0.04–1.83
Field capacity (cm^3 cm^{-3})	0.11–0.56
Wilting point (cm^3 cm^{-3})	0.04–0.48
Soil organic carbon (%)	0.01–30.64
pH	4.0–10.1
Total nitrogen content (%)	0.00–1.10

Field management data mainly include observation of phenology and yield components of winter wheat at each station, as well as the field management measures, such as varieties, irrigation, and fertilization. The field management data for 1982–2017 were from experiments conducted at the national agrometeorological stations, which are maintained by the Chinese Meteorological Administration. For the phenology, the dates of sowing (BBCH 00), emergence (BBCH 10), dormancy (start of dormancy), green up (end of dormancy), anthesis (BBCH 61) and maturity (BBCH 89) were recorded [15]. For the yield, the spikelet number, the infertile spikelet rate, the grain number, the thousand grain weight, and the plot grain yield were recorded. For irrigation and fertilization, the dates and quantities were recorded.

Groundwater data were obtained from the Atlas of Groundwater Resources and Environment in China [16], surface water resource availability and precipitation data were obtained from the Water Resources Reports of provinces and cities in the NCP, as well as the Water Resources Reports of the Haihe River, the Yellow River, and the Huaihe River from 2011 to 2014.

2.3. Methods

2.3.1. DSSAT Model

DSSAT is one of the widely used crop models, and CERES-Wheat is the sub-model developed specifically for wheat [17]. The model runs on DSSAT-CSM (cropping system model) public platform as a module, and uses the meteorological and soil database and soil moisture, nitrogen, and carbon balance module to simulate wheat growth and development, yield formation, nitrogen-carbon-water balance process [17]. The simulation process involves light interception and photosynthesis, nutrient absorption and root activity, dry matter distribution, water absorption and transpiration, growth and respiration, leaf area growth, development and organ formation, senescence, field management measures, etc. There are four parts of data needed for the operation of the CERES–Wheat model, which are meteorological data, soil data, crop variety data, and field management data. This model has a complete consideration of soil water balance processes and physical mechanisms, it has been validated for the assessment of wheat production [18].

After the data were prepared, we calibrated the model by using field experimental data for the nine stations. After calibration, we validated the model by comparing the observed data on phenology and yield during the other years (Table 2).

Table 2. Experimental dataset for CERES-Wheat calibration and validation at nine stations.

Station	Calibration Dataset	Validation Dataset
Tangshan	1997–2000	2004–2007
Huanghua	1995–1999	2004–2009
Luancheng	2001	2002, 2003
Huimin	2001–2004	2005–2009
Nangong	2002, 2003	2004–2005
Ganyu	2005, 2006	2007–2008
Shangqiu	1997	1998
Zhumadian	1987, 1989, 1990	1993–1995
Shouxian	2006	2007

Then we employed the Normalized Root Mean Square Error (NRMSE) and Consistency Index (D value) to check the agreement between observed and simulated values. The formulas are as follows:

$$\mathrm{NRMSE} = \frac{\sqrt{\sum_{i=1}^{n}(S_i - R_i)^2/n}}{\overline{R}} \times 100\% \quad (1)$$

$$D = 1 - \left[\frac{\sum_{i=1}^{n}(S_i - R_i)^2}{\sum_{i=1}^{n}\left(\left|S_i + \overline{R}\right| + \left|R_i - \overline{R}\right|\right)^2}\right] \quad (2)$$

where S_i is the simulated value; R_i is the observed value; $\overline{R}$ is the average of observed values; n is the sample size. The simulation is excellent if the NRMSE is less than 10%; the simulation is generally accurate if the NRMSE is between 20% and 30%; the simulation is poor if the NRMSE is greater than 30% [19]. The D value ranges from 0 to 1, a value closer to 1 indicates perfect agreement between the observed value and simulated value, while a value closer to 0 indicates poor predictability [20].

After validation, we used the CERES-Wheat model to simulate the yield and WUE under different irrigation levels (from 40 mm to 320 mm, with an interval gradient of 40 mm) for 36 years (1982–2017) at nine representative stations in the NCP, to explore the optimal amount of irrigation for high yield and water saving of the winter wheat. For each station, the irrigation dates and frequency were set according to the observed irrigation management from experiments conducted at the nine agrometeorological stations, meanwhile, based on the constraint of the total amount of given irrigation levels, the irrigation amount was set according to the percentage of the observed irrigation management from experiments on the nine agrometeorological stations.

2.3.2. Optimal Irrigation Amount for High Yield of the Winter Wheat (OI_y)

The yield was directly simulated by the CERES-Wheat model, which was set to be affected by irrigation only, the nutrients, pests, and other factors were not taken into account. The optimal irrigation amount for high yield was the irrigation value corresponding to the maximum yield of the winter wheat.

2.3.3. Optimal Irrigation Amount for Water Saving of the Winter Wheat (OI_{WUE})

WUE was derived from the ratio of yield to evapotranspiration. It was used to evaluate optimum irrigation management to ensure the most efficient use of water resources. The formula is as follows:

$$WUE = \frac{Y}{ET} \tag{3}$$

where WUE is the water use efficiency; Y is the yield of winter wheat; ET is the evapotranspiration. The yield and evapotranspiration were based on the simulation from the CERES-Wheat model. The optimal irrigation amount for water saving was the irrigation value corresponding to the maximum WUE of winter wheat.

2.3.4. Optimal Irrigation Amount for the Trade-Off between High Yield and Water Saving of the Winter Wheat (OI_t)

The optimal amount of irrigation for high yield was not necessarily equal to that value for water saving. The trade-off between high yield and water saving should be considered if we want to complete the two objectives simultaneously. Using the method of Zheng et al. [21], yield and WUE at different gradients of irrigation levels at each station were standardized, and the irrigation amount that achieved the maximum value of normalized yield and WUE was determined as the optimal irrigation amount for the trade-off between the high yield and water saving. The formula is as follows:

$$\lim_{I \to OI_t} \left(\frac{Y}{Y_{max}} + \frac{WUE}{WUE_{max}} \right) = 2 \tag{4}$$

where Y and WUE are the yield and WUE simulated by CERES-Wheat model under different irrigation gradients; Y_{max} and WUE_{max} are the maximum values of yield and WUE over the growing season at each station, respectively; OI_t is the optimal irrigation amount for the trade-off between high yield and water saving of the winter wheat.

2.3.5. Optimal Irrigation Amount Constrained by the Irrigation Availability (OI)

The calculation of irrigation availability was referred to Lei et al. [22], with the following equations:

$$W_i = W_s + W_g \times k - W_d \tag{5}$$

$$W_d = \rho \times W_i \tag{6}$$

where W_i is the available irrigation amount; W_s is the available surface water; W_g is the amount of exploitable coefficient groundwater; k is the proportion of agricultural water to groundwater; W_d is the duplication of surface water and groundwater; ρ is the exploitable coefficient, which is the ratio of exploitable groundwater to the total amount of groundwater; W_i is the infiltration. Since deep groundwater has few recharge sources, a long recovery period, and a very slow renewal rate, it can be regarded as a non-renewable resource. Therefore, the deep groundwater is not suitable for irrigation and not included in the calculation.

For the purpose of water saving and sustainable agricultural production, irrigation of winter wheat should use only the available irrigation without over-exploitation of groundwater. Taking irrigation availability as a constraint, the final optimal irrigation amount was determined by comparing the OI_t with the available irrigation amount at the corresponding station. If the available irrigation amount is greater than or equal to the OI_t, which indicates that the water resources can support the OI_t to complete high yield and water saving simultaneously, then take the OI_t as the final optimal irrigation amount. If the available irrigation amount is less than the OI_t, then the production of winter wheat is irrigation constrained, the final optimal irrigation amount should be determined according to the yield and WUE changes with irrigation levels, as well as the available irrigation amount.

3. Results

3.1. Validation of CERES-Wheat Model

For the anthesis of winter wheat in the NCP, the simulated anthesis (from 172 days to 227 days after sowing) was very close to the observed values (from day 176 days to 223 days after sowing), the simulated anthesis agreed well with the observed anthesis with NRMSE of 1.51% and D value of 0.98 (Table 3). Similarly, simulated maturity (from 209 days to 257 days after sowing) was well matched with the observations (from 210 days to 257 days after sowing), with NRMSE of 0.95% and D value of 0.99, respectively. Although the NRMSE (14.89%) and D value (0.96) of the yield were not as high as the values of anthesis and maturity, the observed yield ranged from 1650 kg ha^{-1} to 7395 kg ha^{-1}, and the simulated yield ranged from 1030 kg ha^{-1} to 7577 kg ha^{-1} (Table 3), the model also exhibited the agreement between the simulation and observation. Overall, the stability and accuracy of the calibrated model were confirmed by the above evaluation, especially for the anthesis and maturity. The calibrated model can be applied to simulate the yield and WUE of winter wheat in response to irrigation management in the NCP.

Table 3. Validation of simulation on anthesis, maturity, and yield of winter wheat in the North China Plain.

Item	Observed Value	Simulated Value	NRMSE	D Value
Anthesis (BBCH 61)	176–223 d after sowing	172–227 d after sowing	1.51%	0.98
Maturity (BBCH 89)	210–257 d after sowing	209–257 d after sowing	0.95%	0.99
Yield	1650–7395 kg ha^{-1}	1030–7577 kg ha^{-1}	14.89%	0.96

Notes: The NRMSE is the Normalized Root Mean Square Error between the observed values and simulated values; D value is the Consistency Index between the observed values and simulated values; BBCH is the Biologische Bundesanstalt, Bundessortenamt, Chemische Industrie. This code is recommended for phenological observations.

3.2. Optimal Irrigation Amount for High Yield of Winter Wheat (OI_y)

Low yield occurred in all stations with rainfed management, the range of no irrigation yields was from 2411 kg ha^{-1} to 7679 kg ha^{-1} (Figure 2). For each station in the NCP, yield exhibited an increasing trend with the increase in irrigation. However, when irrigation reached a certain level, the yield change leveled off, indicating that the high yield of winter wheat greatly relied on irrigation in the NCP (Figure 2). Conversely, excessive water was not beneficial to yield increase due to the Law of Diminishing Returns. For the maximum yield of winter wheat, Nangong and Tangshan stations required more irrigation (240 mm) than other stations, the maximum yield could reach 10,917 kg ha^{-1} and 9346 kg ha^{-1}, respectively. Luancheng, Huimin and Huanghua stations required an equal amount of irrigation (160 mm), the maximum yields at the three stations were 8669 kg ha^{-1}, 8334 kg ha^{-1} and 5856 kg ha^{-1}, respectively. Whereas the amounts of irrigation required at Ganyu and Zhumadian stations were relatively small (120 mm), and the highest yields were 8851 kg ha^{-1} and 7333 kg ha^{-1}, respectively. Shouxian and Shangqiu stations had the lowest optimal irrigation (80 mm) among the nine stations, their maximum yields were 8260 kg ha^{-1} and 6912 kg ha^{-1}, respectively.

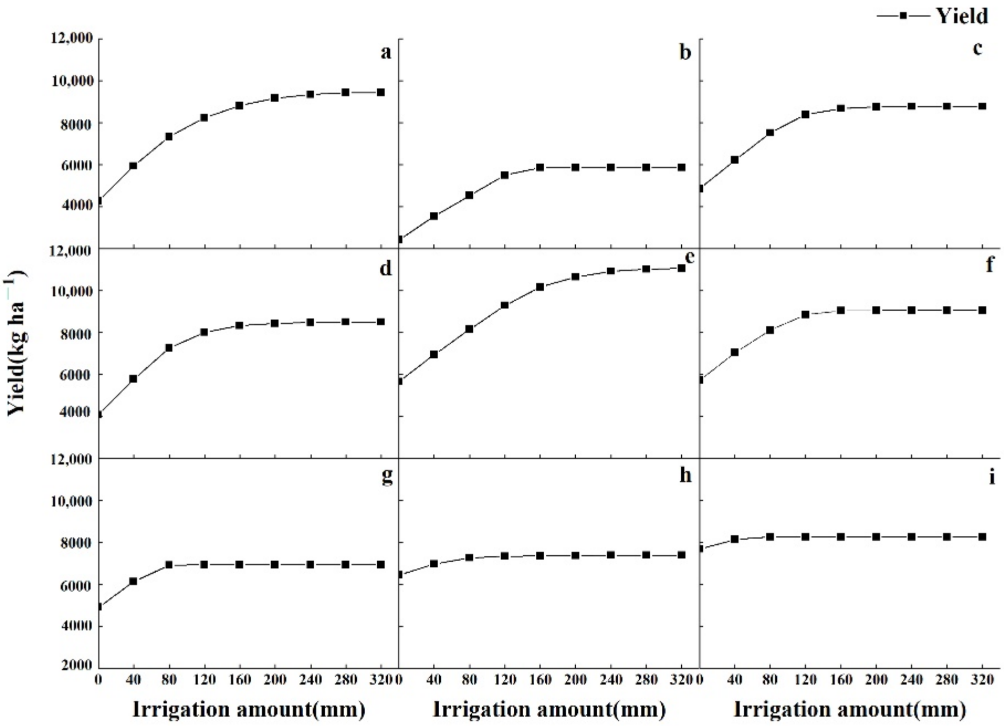

Figure 2. Changes in winter wheat yield with irrigation levels in the North China Plain. (**a**) Tangshan, (**b**) Huanghua, (**c**) Luancheng, (**d**) Huimin, (**e**) Nangong, (**f**) Ganyu, (**g**) Shangqiu, (**h**) Zhumadian, (**i**) Shouxian.

Spatially, taking the Yellow River as the dividing line, the optimal irrigation amounts in the northern five stations (Tangshan, Huanghua, Luancheng, Huimin, and Nangong stations) were all greater than 160 mm (Figure 2). Nevertheless, the range of optimal irrigation amounts in the southern four stations (Ganyu, Shangqiu, Zhumadian, and Shouxian stations) was from 80 mm to 120 mm, the difference between the southern and northern stations probably due to the spatial variability of precipitation, which drove the variation in water demand for irrigation.

3.3. *Optimal Irrigation Amount for Water Saving of the Winter Wheat (OI_{WUE})*

For each station in the NCP, similarly to the trend of yield change, the WUE increased gradually with the irrigation level, and then leveled off, stopped rising, or even started to decline after reaching a certain threshold (Figure 3). WUE decreased with more irrigation because the increase in irrigation was greater as compared to the increase in yield. For the maximum WUE of winter wheat, Nangong and Tangshan stations demanded the highest irrigation amount in the region (200 mm), and their maximum WUEs were 2.4 kg m^{-3} and 2.2 kg m^{-3}, respectively. When the winter wheat acquired 160 mm irrigation in Huanghua station, its WUE reached the maximum (1.6 kg m^{-3}). In addition, the irrigation amount was required for 120 mm in Luancheng, Huimin and Ganyu stations for the optimal WUE, the maximum WUE of winter wheat was 2.3 kg m^{-3}, 2.3 kg m^{-3} and 1.9 kg m^{-3}, respectively. While the maximum WUE of winter wheat was 2.0 kg m^{-3} and 1.9 kg m^{-3} at Shangqiu and Zhumadian stations, which required relatively less irrigation, 80 mm and 40 mm, respectively.

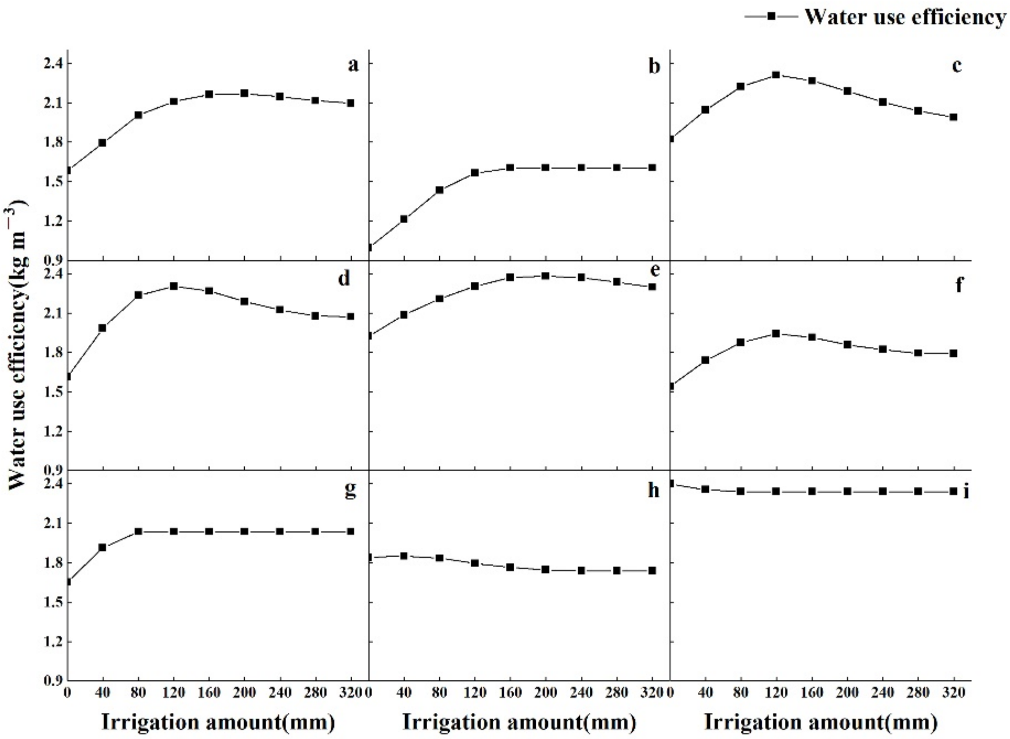

Figure 3. Changes in water use efficiency of winter wheat with irrigation levels in the North China Plain. (**a**) Tangshan, (**b**) Huanghua, (**c**) Luancheng, (**d**) Huimin, (**e**) Nangong, (**f**) Ganyu, (**g**) Shangqiu, (**h**) Zhumadian, (**i**) Shouxian.

The optimal irrigation amount for water saving (OI_{WUE}) had a similar spatial pattern to the optimal irrigation amount for high yield (OI_y), OI_{WUE} in the northern stations varied from 120 mm to 200 mm, while the OI_{WUE} range in southern stations was between 0 mm and 120 mm. For the southern station, the abundant precipitation can satisfy the water demand of winter wheat, so the increase in irrigation amount significantly decreased the WUE.

3.4. *Optimal Irrigation Amount for the Trade-Off between High Yield and Water Saving (OI_t)*

In terms of the relationship among OI_y, OI_{WUE}, and OI_t in each station, values of the three types of optimal irrigation amount were coincidentally equal in Huanghua, Ganyu, and Shangqiu stations, thus, the OI_t in Huanghua, Ganyu, and Shangqiu stations were 160 mm, 120 mm and 80 mm, respectively. With this irrigation management, these stations can complete the perfect combination of high yield and water saving (Figure 4). For the remaining six stations, the OI_y values were all greater than the OI_{WUE} values. After calculation, the OI_t values of Tangshan station (240 mm), Luancheng station (160 mm), Huimin station (160 mm), Nangong station (240 mm), and Shouxian station (80 mm) were all equal to their own OI_y. Thus, the trade-offs in these stations were at the expense of falling WUE to some extent. Nevertheless, Zhumadian station was a special case, for the OI_t (80 mm) was between the OI_y (120 mm) and the OI_{WUE} (40 mm), its trade-off was the optimal configuration with losses of the maximum yield and WUE (Figure 4).

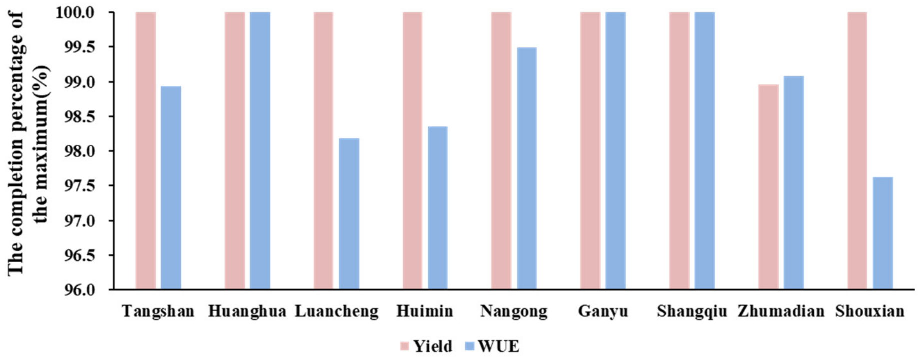

Figure 4. The completion percentage of the maximum yield and water use efficiency (WUE) based on the OI_t.

In terms of the spatial pattern, the OI_t values in the four southern stations (Ganyu, Shangqiu, Zhumadian and Shouxian stations) were all no greater than 120 mm, while the OI_t values of the five northern stations (Tangshan, Huanghua, Luancheng, Huimin and Nangong stations) were all greater than these in the southern stations, varied from 160 mm to 240 mm (Figure 5). The OI_t showed a similar spatial pattern to the OI_y and OI_{WUE}.

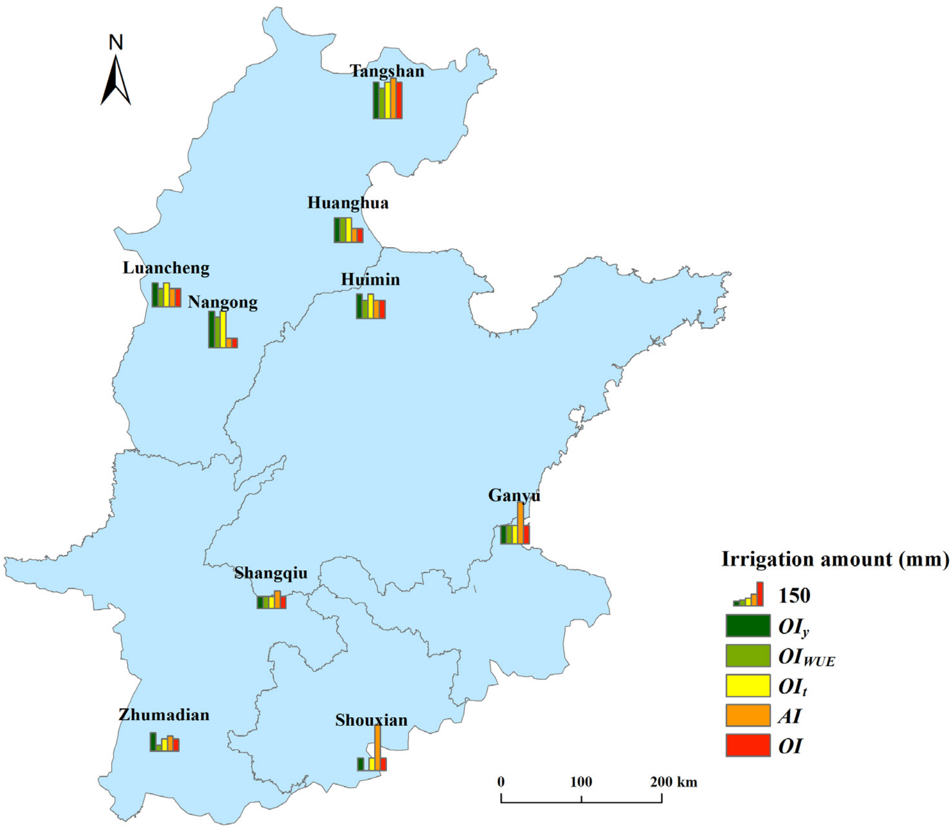

Figure 5. The optimal irrigation amount and the available irrigation amount of winter wheat in the North China Plain. Notes: OI_y is the optimal irrigation amount for a high yield of winter wheat; OI_{WUE} is the optimal irrigation amount for water saving of winter wheat; OI_t is the optimal irrigation amount for the trade-off between high yield and water saving; AI is the available irrigation amount; OI is the final optimal irrigation amount constrained by the available irrigation amount.

Under the irrigation management of OI_t, eight stations can maintain 100% of the maximum yield except for Zhumadian station, the loss percentage of yield in Zhumadian station was only 1.04%. In addition to the 100% of the maximum yield, Huanghua, Ganyu, and Shangqiu stations can simultaneously complete 100% of the maximum WUE. Besides, the completion percentages of the maximum WUE in the Nangong and Zhumadian stations were greater than 99%, and the values in Tangshan, Luancheng, and Huimin stations were all higher than 98%. Although Shouxian station had the highest loss percentage of the maximum WUE, it was still less than 2.5%. In conclusion, the OI_t contributed to the best yield and WUE of winter wheat for all the nine stations in the NCP, the OI_t can maximize the co-benefits of high yield and water saving to the greatest extent possible, it is a suitable choice for considering both yield and efficiency.

3.5. Optimal Irrigation Amount Constrained by the Irrigation Availability (OI)

Spatially, the irrigation availability in the NCP was generally high in the south and low in the north. Among these stations, Nangong and Huanghua stations had the least available irrigation amount (62 mm and 91 mm), because they are in the Heilonggang area, which has the largest groundwater depletion in the world. Tangshan station (267 mm) in the coastal plain of eastern Hebei Province, Ganyu station (273 mm) in the low plain of Xu-Huai of Jiangsu Province, and Shouxian station (300 mm) in the plain of northern Anhui Province had enough available water resources, they were all greater than 200 mm. The available irrigation amounts at the remaining stations (Zhumadian, Shangqiu, Luancheng, and Huimin stations) varied from 100 mm to 121 mm (Figure 6).

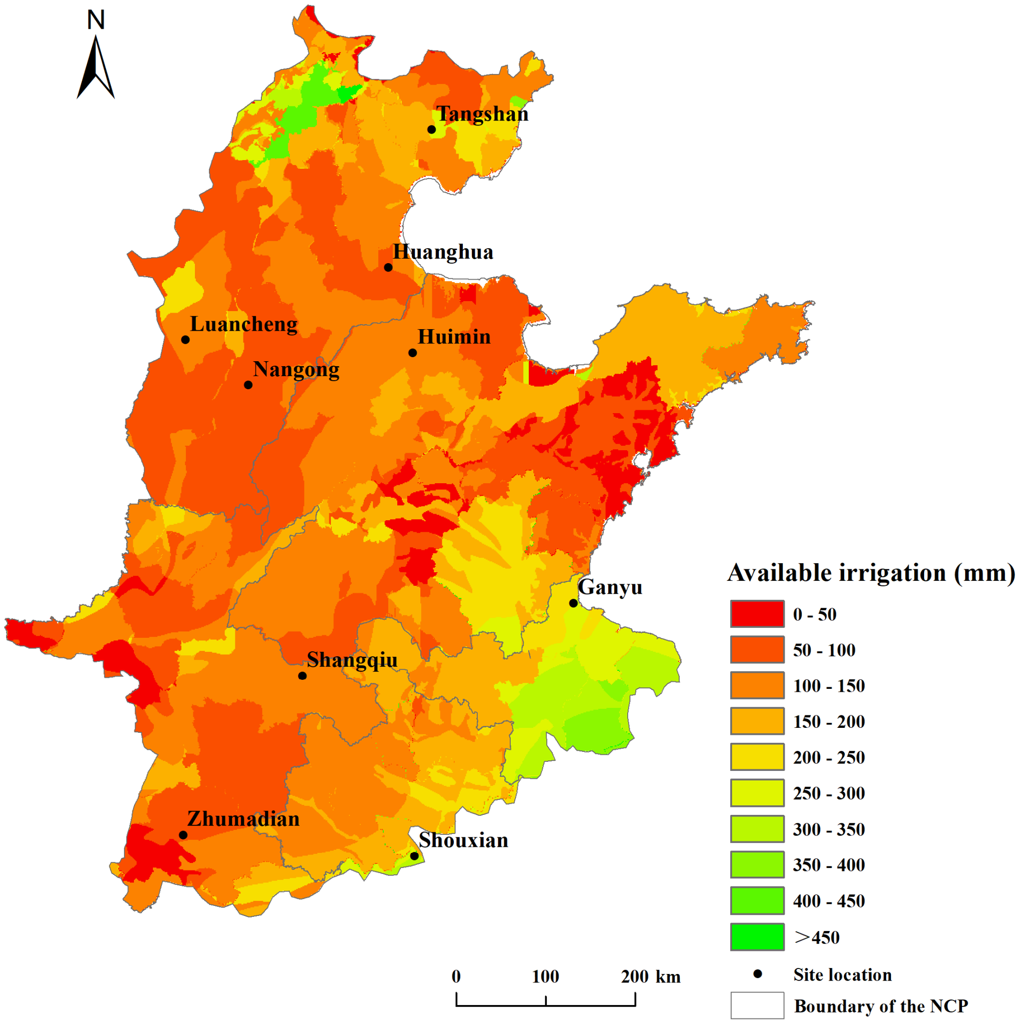

Figure 6. The irrigation availability of winter wheat in the North China Plain.

Compared with the OI_t, the irrigation availability was abundant for the southern stations (Ganyu, Shangqiu, Zhumadian, and Shouxian stations) and Tangshan station, so the final optimal irrigation amount (OI) was equal to the OI_t in the five stations (Figure 5), that is, the OI of the Tangshan and Ganyu stations was 240 mm and 120 mm, respectively, Shangqiu, Zhumadian, and Shouxian stations had the consistent value of OI (80 mm). Nevertheless, four stations in the northern region (Huanghua, Luancheng, Huimin, and Nangong stations) are now in the area of serious groundwater over-exploitation, the available irrigation amount was less than their own OI_t, that is, the water resources cannot supply sufficient irrigation for winter wheat to complete the trade-off between high yield and water saving, so the final optimal irrigation should have binding constraints on water availability. After calculation, the Nangong and Huanghua stations had the lowest OI, 62 mm and 91 mm, respectively; Luancheng (120 mm) and Huimin (121 mm) stations had close values in final optimal irrigation. Due to the differences in groundwater constraints, there was no obvious spatial pattern of optimal irrigation amount.

With the final optimal irrigation amount, for the yield, Tangshan, Ganyu, Shangqiu, and Shouxian stations can complete 100% of the maximum yield; the completion percentages of Luancheng, Huimin, and Zhumadian stations were all greater than 96%; while the Nangong and Huanghua stations had the highest loss of yield, they can only complete 69.72% and 81.87% of the maximum yield, respectively (Figure 7). For the WUE, Luancheng, Huimin, Ganyu, and Shangqiu stations can obtain 100% of the maximum WUE, Nangong and Huanghua stations still had the lowest completion percentage (90.46% and 91.58%), completion percentages of the rest of stations were all greater than 97.5%. In general, with this irrigation management, Ganyu and Shangqiu stations can simultaneously complete 100% of yield and WUE optimization; Tangshan, Luancheng, Huimin, Shouxian, and Zhumadian stations had a slight loss in the yield or WUE. The above seven stations did not lose much yield or efficiency within the irrigation constraints. Nevertheless, the yield and WUE at Nangong and Huanghua stations were greatly limited by water availability. Consequently, appropriate fallowing or adjustment of cropping systems is recommended to protect the local water ecosystem.

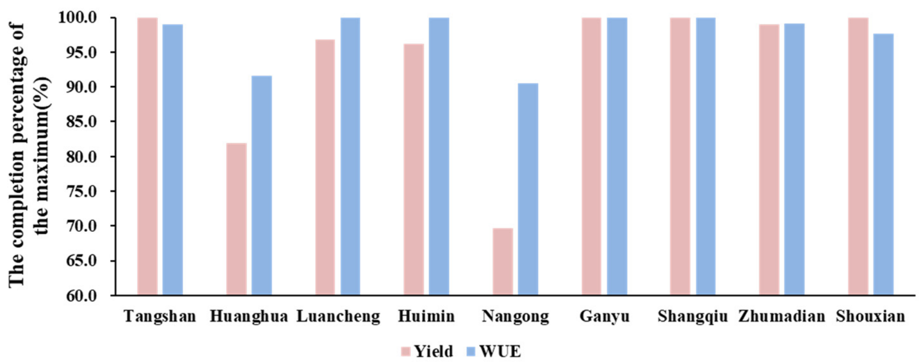

Figure 7. The completion percentage of the maximum yield and water use efficiency (WUE) based on the OI.

4. Discussion

In the NCP, irrigation is of paramount importance to increasing productivity for winter wheat, investigation of the optimal irrigation amount should consider the natural carrying capacity of water resources. In this study, we simulated the variation of yield and WUE with different irrigation levels by using the CERES-Wheat model at nine representative stations in the NCP. Then we determined the optimal irrigation amount for high yield, water saving, and the trade-off between high yield and water saving of winter wheat. Subsequently, based on the equilibrium relationship between irrigation demand and the natural carrying capacity of water resources, we investigated the optimal irrigation amount under the constraint of irrigation availability. The optimization of irrigation strategies is beneficial for wheat production and water conservation in the NCP.

Water is a dominant driver affecting yield, and it has been demonstrated that winter wheat yield had a non-linear relationship with irrigation amount, excessive irrigation did not contribute to a continuous increase in yield [23], and our results also supported that. The yield growth may be inhibited by the decrease in soil permeability due to excess water and the lack of oxygen in the root system of winter wheat. Aiming at a high yield, the optimal irrigation amount for winter wheat at nine stations in the NCP ranged from 80 mm to 240 mm. This was consistent with the field experimental results in Xinxiang station, which revealed the 175–180 mm optimal irrigation for a high yield of winter wheat in the NCP [24].

In addition to yield, we chose WUE to investigate the optimal irrigation amount for winter wheat. The WUE showed an increasing trend and then decreased with the irrigation increase. When the winter wheat is stressed by the water, WUE increases with irrigation increase, while irrigation exceeds a certain threshold, winter wheat evapotranspiration no longer changes significantly, and excessive irrigation will leach into the ground or form surface runoff. Taking WUE as the criterion, Zhang et al. [25] concluded that the optimal irrigation amount of winter wheat in the NCP ranged from 60 mm to 140 mm. Wang et al. [26] suggested that the optimal irrigation amount at Beijing station was between 192 mm and 245 mm. In the study of Ma et al. [27], the optimal irrigation amount for winter wheat in the NCP was between 60 mm and 300 mm, being 70–210 mm at the Luancheng station. Our finding also suggested that the optimal irrigation amount for winter wheat varied from 0 mm to 200 mm, with 120 mm at the Luancheng station.

The OI_t aimed at the unification and optimization of maximum yield and WUE. It has been shown that the maximum reached by yield and WUE with irrigation level did not overlap [28]. In this study, we also concluded that WUE was maximized before yield. Compared to the OI_y, the OI_{WUE} was reduced by 17% to 67%, indicating the water-saving trend. After the trade-off, the OI_t contributed to the best yield and WUE for winter wheat for all nine stations in the NCP, varying from 80 mm to 240 mm. Similar conclusions can be found in previous studies. Based on the APSIM model, Zheng et al. [21] investigated that the OI_t ranged from 3 mm to 286 mm. Moreover, the OI_t of the Luancheng station in another study (202 mm) also had a close value to our study (160 mm) [29].

We considered the sustainable use of groundwater as an upper bound for winter wheat irrigation in this study. Results showed that the available water resources for irrigation exhibited a distribution trend of high in the south and low in the north, revealing a consistent spatial pattern to Lei et al. [22]. With the rapid depletion of groundwater in the NCP, agricultural production has entered a dilemma of food security and water security. This study showed that the irrigation-constrained areas were mainly concentrated in the groundwater over-exploitation area (especially the Heilonggang area). For the regions suffering from water limitations, we should reduce the agricultural intensification, and carry out appropriate fallowing or adjustment of cropping systems to alleviate the groundwater crisis. Meanwhile, for the regions with abundant water resources for irrigation, which were mainly located in the northern Anhui Plain and the low Xu-Huai Plain in the southern part of the NCP, the potential production needs to be maximized to ameliorate the yield losses from the water-scarce regions [30].

Adjustment of the cropping systems is an effective measure to save valuable groundwater for sustainability in over-exploited aquifers. A study conducted by Davis et al. [31] showed that the optimization of cropping structure would save 12–14% of irrigation water at a global scale. Thus, the Chinese government launched the Seasonal Land Fallowing Policy in the NCP in 2014, designed to mitigate serious groundwater over-exploitation. Analysis showed that the policy reduced groundwater consumption and contributed to real water saving [32]. Besides, similar irrigation strategies had been adopted to mitigate groundwater depletion, for example, deficit irrigation [8], drip irrigation systems under the plastic mulch [33], micro-sprinkling [34], and adjustment of planting density [35]. A study concluded that combining all agricultural management could reduce groundwater exploitation intensity by around 74.58% to 96.95%, resulting that groundwater could recover to the original health level nearly in the NCP [11].

In addition to promoting water conservation technologies and implementing the relevant water use policies from the demand side, on the supply side, it encourages water users to replace groundwater with surface water delivered by the central South-to-North Water Diversion, to alleviate the water stress and groundwater storage deficit in the NCP. A study conducted by Long et al. [36] found, within the context of climate variability and policy implications, water diverted to Beijing reduces cumulative groundwater depletion by 3.6 km^3, accounting for 40% of total groundwater storage restoration between 2006 and 2018, meanwhile, increased precipitation and policy-induced contributed about 2.7 km^3 (~30%) and 2.8 km^3 (~30%) to the groundwater storage recovery [36]. It proves the important role of South-to-North Water Diversion in groundwater restoration. Overall, more efforts need to be explored to save valuable groundwater for the sustainability of irrigated agriculture in the NCP.

Our analysis was subject to considerable uncertainties. Except for the irrigation management, the rest of the cultivation conditions were assumed as optimal in our study. In general, climate, soil, cultivation practices, pests, and diseases all have influences on the optimal irrigation amount of winter wheat. Thus, the optimal irrigation of winter wheat can be further analyzed based on specific considerations of regional differences in cultivation. Furthermore, the results of the optimal irrigation should be applied to the field for supporting evidence, in order to better guide practice for local farmers. In addition, the optimal irrigation amount can be determined by considering the greenhouse gas emissions [37], soil moisture, and carbon footprint [38], in combination with the precipitation pattern, to make more targeted recommendations in the future.

5. Conclusions

For the NCP, the OI_y ranged from 80 mm to 240 mm, and the OI_{WUE} varied from 0 mm to 200 mm. After the trade-off between yield and WUE, the OI_t was between 80 mm and 240 mm, which maximized the co-benefit of high yield and water saving.

The available irrigation amount varied from 62 mm to 300 mm in the NCP. Generally, southern stations had higher water availability than northern stations, and stations located in the Heilonggang area (Nangong and Huanghua stations) had the lowest irrigation availability. As the region has the most severe groundwater depletion in the world, the optimal irrigation amount needs to be constrained by water availability. Based on the equilibrium relationship between irrigation and the natural carrying capacity of water resources, we determined the final optimal irrigation amount (62–240 mm) by the irrigation availability constraint. Yield and WUE were greatly affected in Huanghua and Nangong stations with the final optimal irrigation amount; however, the rest stations can maintain more than 96% of the maximum yield and 97.5% of the maximum WUE and complete the optimization of both high productivity and water saving.

For the water-scarce regions, the irrigation availability cannot support the optimization of yield and WUE, and it is recommended to moderately fallow, deficit irrigation, or implement appropriate cropping system adjustments, as well as use alternative water resources to ensure water security. Meanwhile, we should strengthen the production potential of the southern part of the NCP and appropriately consider the global wheat trade market for capacity substitution to maintain the sustainable use of regional water resources and grain production.

Author Contributions: Conceptualization, X.S. and W.S.; methodology, X.S. and W.S.; software, N.D. and M.W.; validation, N.D. and M.W.; visualization, N.D. and M.W.; writing—original draft preparation, X.S.; writing—review and editing, W.S.; supervision, X.S. and W.S.; funding acquisition, W.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key Research and Development Program of China (2022YFB3903504), the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant No. XDA20010202 and No. XDA23100202), and the Science Fund for Creative Research Groups of the National Natural Science Foundation of China (Grant No. 72221002).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Lei, M.; Zhang, Y.Q.; Dang, Y.X.; Kong, X.B.; Yao, J.T. Does crop rotation enhance groundwater health? A review of the Winter Wheat Fallow Policy in the North China Plain. *Water* **2019**, *11*, 2416. [CrossRef]
2. Liu, H.J.; Yu, L.P.; Luo, Y.; Wang, X.P.; Huang, G.H. Responses of winter wheat evapotranspiration and yield to sprinkler irrigation regimes. *Agric. Water Manag.* **2011**, *98*, 483–492. [CrossRef]
3. Sun, H.Y.; Shen, Y.J.; Yu, Q.; Flerchinger, G.N.; Zhang, Y.Q.; Liu, C.M.; Zhang, X.Y. Effect of precipitation change on water balance and WUE of the winter wheat-summer maize rotation in the North China Plain. *Agric. Water Manag.* **2010**, *97*, 1139–1145. [CrossRef]
4. Boumaza, K.; Kalboussi, N.; Rapaport, A.; Roux, S.; Sinfort, C. Optimal control of a crop irrigation model under water scarcity. *Optim. Contr. Appl. Met.* **2021**, *42*, 1612–1631. [CrossRef]
5. Zhang, C.; Xie, Z.A.; Wang, Q.J.; Tang, M.; Feng, S.Y.; Cai, H.J. AquaCrop modeling to explore optimal irrigation of winter wheat for improving grain yield and water productivity. *Agric. Water Manag.* **2022**, *266*, 107580. [CrossRef]
6. Yang, X.L.; Wang, G.Y.; Chen, Y.Q.; Sui, P.; Pacenka, S.; Steenhuis, T.S.; Siddique, K.H.M. Reduced groundwater use and increased grain production by optimized irrigation scheduling in winter wheat-summer maize double cropping system-A 16-year field study in North China Plain. *Field Crop. Res.* **2022**, *275*, 108364. [CrossRef]
7. Xu, X.X.; Zhang, M.; Li, J.P.; Liu, Z.Q.; Zhao, Z.G.; Zhang, Y.H.; Zhou, S.L.; Wang, Z.M. Improving water use efficiency and grain yield of winter wheat by optimizing irrigations in the North China Plain. *Field Crop. Res.* **2018**, *221*, 219–227. [CrossRef]
8. Kheir, A.M.S.; Alrajhi, A.A.; Ghoneim, A.M.; Ali, E.F.; Magrashi, A.; Zoghdan, M.G.; Sedhom, A.M.; Abdelkhalik, F.; Ahmed, E.; Fahmy, G.; et al. Modeling deficit irrigation-based evapotranspiration optimizes wheat yield and water productivity in arid regions. *Agric. Water Manag.* **2021**, *256*, 107122. [CrossRef]
9. Aluoch, S.O.; Li, Z.T.; Li, X.X.; Hu, C.S.; Mburu, D.M.; Yang, J.Y.; Xu, Q.S.; Yang, Y.Z.; Su, H.X. Effect of mineral N fertilizer and organic input on maize yield and soil water content for assessing optimal N and irrigation rates in Central Kenya. *Field Crop. Res.* **2022**, *277*, 108420. [CrossRef]
10. Wang, Y.Q.; Zhang, Y.H.; Zhang, R.; Li, J.P.; Zhang, M.; Zhou, S.L.; Wang, Z.M. Reduced irrigation increases the water use efficiency and productivity of winter wheat-summer maize rotation on the North China Plain. *Sci. Total Environ.* **2018**, *618*, 112–120. [CrossRef]
11. Chen, X.Z.; Wang, P.X.; Muhammad, T.; Xu, Z.C.; Li, Y.K. Subsystem-level groundwater footprint assessment in North China Plain–The world's largest groundwater depression cone. *Ecol. Indic.* **2020**, *117*, 106662. [CrossRef]
12. Liu, R.L.; Zhong, B.; Li, X.P.; Zheng, K.Y.; Liang, H.; Cao, J.M.; Yan, X.; Lyu, H.X. Analysis of groundwater changes (2003–2020) in the North China Plain using geodetic measurements. *J. Hydrol.-Reg. Stud.* **2022**, *41*, 101085. [CrossRef]
13. Van, L.P.E.; Sanchez, G.A. Mapping PAR using MODIS atmosphere products. *Remote Sens. Environ.* **2005**, *94*, 554–563.
14. Zhang, H.; Tao, F.L.; Zhou, G.S. Potential yields, yield gaps, and optimal agronomic management practices for rice production systems in different regions of China. *Agric. Syst.* **2019**, *171*, 100–112. [CrossRef]
15. Xiao, D.P.; Tao, F.L.; Liu, Y.J.; Shi, W.J.; Wang, M.; Liu, F.S.; Zhang, S.; Zhu, Z. Observed changes in winter wheat phenology in the North China Plain for 1981–2009. *Int. J. Biometeorol.* **2013**, *57*, 275–285. [CrossRef] [PubMed]
16. Zhang, Z.H.; Li, L.R. *Atlas of Groundwater Resources and Environment in China*; China Map Press: Beijing, China, 2004.
17. Jones, J.W.; Hoogenboom, G.; Porter, C.H.; Boote, K.J.; Batchelor, W.D.; Hunt, L.A.; Wilkens, P.W.; Singh, U.; Gijsman, A.J.; Ritchie, J.T. The DSSAT cropping system model. *Eur. J. Agron.* **2003**, *18*, 235–265. [CrossRef]
18. Zhou, L.L.; Liao, S.H.; Wang, Z.M.; Wang, P.; Zhang, Y.H.; Yan, H.J.; Gao, Z.; Shen, S.; Liang, X.G.; Wang, J.H.; et al. A simulation of winter wheat crop responses to irrigation management using CERES-Wheat model in the North China Plain. *J. Integr. Agric.* **2018**, *17*, 1181–1193. [CrossRef]
19. Bannayan, M.; Hoogenboom, G. Using pattern recognition for estimating cultivar coefficients of a crop simulation model. *Field Crop. Res.* **2009**, *111*, 290–302. [CrossRef]
20. Willmott, C.J. Some comments on the evaluation of model performance. *Bull. Am. Meteorol. Soc.* **1982**, *63*, 1309–1313. [CrossRef]
21. Zheng, J.Q.; Wang, J.; Ren, W.; Tang, J.Z.; He, D.; Huang, M.X.; Bai, H.Q.; Wu, B.J. Modeling the impacts of climate, soil, and cultivar on optimal irrigation amount of winter wheat in the North China Plain. *Agron. J.* **2020**, *112*, 1176–1189. [CrossRef]
22. Lei, M.; Kong, X.B.; Wang, J.N. Estimation of sustainable grain productivity for arable land under water balance in the Huang-Huai-Hai Plain. *Acta Geogr. Sin.* **2018**, *73*, 535–549.

23. Dar, E.A.; Brar, A.S.; Mishra, S.K.; Singh, K.B. Simulating response of wheat to timing and depth of irrigation water in drip irrigation system using CERES-Wheat model. *Field Crop. Res.* **2017**, *214*, 149–163. [CrossRef]
24. Jha, S.K.; Ramatshaba, T.S.; Wang, G.; Liang, Y.; Liu, H.; Gao, Y.; Duan, A.W. Response of growth, yield and water use efficiency of winter wheat to different irrigation methods and scheduling in North China Plain. *Agric. Water Manag.* **2019**, *217*, 292–302.
25. Zhang, X.Y.; Chen, S.Y.; Sun, H.Y.; Pei, D.; Wang, Y.M. Dry matter, harvest index, grain yield and water use efficiency as affected by water supply in winter wheat. *Irrig. Sci.* **2008**, *27*, 1–10. [CrossRef]
26. Wang, X.P.; Huang, G.H.; Yang, J.S.; Huang, Q.Z.; Liu, H.J.; Yu, L.P. An assessment of irrigation practices: Sprinkler irrigation of winter wheat in the North China Plain. *Agric. Water Manag.* **2015**, *159*, 197–208. [CrossRef]
27. Ma, Y.; Feng, S.Y.; Song, X.F. Evaluation of optimal irrigation scheduling and groundwater recharge at representative sites in the North China Plain with SWAP model and field experiments. *Comput. Electron. Agric.* **2015**, *116*, 125–136. [CrossRef]
28. Liu, Y.; Guan, X.K.; Yang, M.D.; Ding, C.M.; Cui, J.Y.; Huang, J.; Mei, F.J.; Wang, H.P.; Wang, T.C. Optimizing the summer maize irrigation schedule in North Henan Province based on the DSSAT model. *Acta Ecol. Sin.* **2019**, *39*, 5348–5358.
29. Wang, H.X.; Zhang, L.; Dawes, W.R.; Liu, C.M. Improving water use efficiency of irrigated crops in the North China Plain–Measurements and modelling. *Agric. Water Manag.* **2001**, *48*, 151–167. [CrossRef]
30. Hu, Y.; Moiwo, J.P.; Yang, Y.H.; Han, S.M.; Yang, Y.M. Agricultural water-saving and sustainable groundwater management in Shijiazhuang Irrigation District, North China Plain. *J. Hydrol.* **2010**, *393*, 219–232. [CrossRef]
31. Davis, K.F.; Rulli, M.C.; Seveso, A.; D'Odorico, P. Increased food production and reduced water use through optimized crop distribution. *Nat. Geosci.* **2017**, *10*, 919–924. [CrossRef]
32. Deng, H.B.; Guan, B.Z.; Wang, J.X.; Zuo, A.; Wang, Z.L.; Sun, T.H. Seasonal Land Fallowing Policy in response to groundwater overdraft in the North China Plain. *Water Altern.* **2021**, *14*, 371–394.
33. Zhang, G.Q.; Liu, C.W.; Xiao, C.H.; Xie, R.Z.; Ming, B.; Hou, P.; Liu, G.Z.; Xu, W.J.; Shen, D.P.; Wang, K.R.; et al. Optimizing water use efficiency and economic return of super high yield spring maize under drip irrigation and plastic mulching in arid areas of China. *Field Crop. Res.* **2017**, *211*, 137–146. [CrossRef]
34. Li, J.P.; Zhang, Z.; Liu, Y.; Yao, C.S.; Song, W.Y.; Xu, X.X.; Zhang, M.; Zhou, A.N.; Gao, Y.M.; Wang, Z.M.; et al. Effects of micro-sprinkling with different irrigation amount on grain yield and water use efficiency of winter wheat in the North China Plain. *Agric. Water Manag.* **2019**, *224*, 105736. [CrossRef]
35. Guo, Q.; Huang, G.M.; Guo, Y.L.; Zhang, M.C.; Zhou, Y.Y.; Duan, L.S. Optimizing irrigation and planting density of spring maize under mulch drip irrigation system in the arid region of Northwest China. *Field Crop. Res.* **2021**, *266*, 108141. [CrossRef]
36. Long, D.; Yang, W.T.; Scanlon, B.R.; Zhao, J.S.; Liu, D.G.; Burek, P.; Pan, Y.; You, L.Z.; Wada, Y. South-to-North Water Diversion stabilizing Beijing's groundwater levels. *Nat. Commun.* **2020**, *11*, 3665. [CrossRef]
37. Zhang, X.; Xiao, G.M.; Li, H.; Wang, L.G.; Wu, S.X.; Wu, W.L.; Meng, F.Q. Mitigation of greenhouse gas emissions through optimized irrigation and nitrogen fertilization in intensively managed wheat-maize production. *Sci. Rep.* **2020**, *10*, 5907. [CrossRef]
38. Gao, J.; Xu, C.C.; Luo, N.; Liu, X.W.; Huang, S.B.; Wang, P. Mitigating global warming potential while coordinating economic benefits by optimizing irrigation managements in maize production. *J. Environ. Manag.* **2021**, *298*, 113474. [CrossRef]