agriculture

Article

Effects of Combined Main Ditch and Field Ditch Control Measures on Crop Yield and Drainage Discharge in the Northern Huaihe River Plain, Anhui Province, China

Rong Tang [1], Xiugui Wang [1,*], Xudong Han [1,*], Yihui Yan [1], Shuang Huang [1], Jiesheng Huang [1], Tao Shen [2], Youzhen Wang [2] and Jia Liu [2]

1 State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China
2 Key Laboratory of Water Conservancy and Water Resources of Anhui Province, Anhui & Huaihe River Institute of Hydraulic Research, Bengbu 233000, China
* Correspondence: wangxg@whu.edu.cn (X.W.); hanxudong@whu.edu.cn (X.H.); Tel.: +86-153-3723-6043 (X.W.); +86-150-7100-2290 (X.H.)

Abstract: Open-ditch controlled drainage is an important water management measure used to reduce drought and waterlogging stress in many areas in the world. Such measures are essential to promote the crop yield, make full use of rainfall resources, reduce regional drainage discharge (Q) and reduce water environmental pollution. To quantify its effects, an open-ditch controlled drainage and crop yield simulation model was developed in an area located in Northern Huaihe River Plain (NHRP), Anhui Province, China. The model was calibrated and validated. The changes in crop yield and Q were simulated under different main-ditch water-depth control schemes, field ditch layout and outlet weir height control schemes from 1991 to 2021. Compared with the current situation, the change in crop yield caused by the main ditch schemes was significantly higher than that caused by the field ditch schemes. The change in Q caused by the field ditch schemes was greater than that caused by the main ditch schemes, with values of 60% and 0.02%, respectively. Combined control schemes could further increase the crop yield and reduce the Q. The results have practical application value for ensuring good crop yields and reducing farmland drainage in the NHRP and other similar regions.

Keywords: controlled drainage; crop yield; farmland drainage; farmland non-point

Citation: Tang, R.; Wang, X.; Han, X.; Yan, Y.; Huang, S.; Huang, J.; Shen, T.; Wang, Y.; Liu, J. Effects of Combined Main Ditch and Field Ditch Control Measures on Crop Yield and Drainage Discharge in the Northern Huaihe River Plain, Anhui Province, China. *Agriculture* **2022**, *12*, 1167. https://doi.org/10.3390/agriculture12081167

Academic Editor: Aliasghar Montazar

Received: 6 July 2022
Accepted: 31 July 2022
Published: 5 August 2022

1. Introduction

In recent years, as a result of climate change, extreme climate events such as extremely high temperatures and heavy rain have occurred more frequently [1,2], which pose a serious threat to agricultural production [3,4] and jeopardize global food production and food security [5,6]. Approximately 70% of the world's water withdrawals are used for agriculture [7,8]; therefore, it is necessary to improve water-use efficiency with the water management measures to meet the increasing water demand caused by future population growth, economic development, urbanization and climate change. A report by the United Nations announced the 17 Sustainable Development Goals of the 2030 Agenda for Sustainable Development, in which Goals 2 and 6 emphasize achieving food security, promoting sustainable agriculture, and ensuring water availability and sustainable management [9]. Therefore, from the perspective of agricultural water management, it is crucial to formulate new water resource management measures [10,11].

Controlled drainage has great potential to save water, control water pollution and increase crop yields, representing the best water management measure for agricultural production in many regions such as Europe and the USA [12,13]. Controlled drainage is an improvement on traditional free drainage, which is realized by installing a structure in the outlet of a drainage ditch or subsurface drain [14]. Controlled drainage plays a positive role in preventing agricultural drought and waterlogging disasters, ensuring the normal growth of crops, making rational use of water resources and promoting economic development [15–17]. Youssef et al. [18] used DRAINMOD and DRAINMOD-NII to simulate the effect of controlled drainage on the hydrology and nitrogen dynamics for 48 sites across the Midwestern United States and found that the average reductions in subsurface drainage and N were 29.4% and 32.3%, respectively. Jouni et al. conducted field experiments with different drainage depths and found that controlled drainage with subsurface drainage not only improved the crop yield but also reduced subsurface drainage flow and nutrients [16]. Li et al. examined the salt leaching effect of natural rainfall in a semiarid irrigation area and found that proper management of the water table through a field ditch system may improve water use efficiency [19]. In addition, Jia et al. evaluated drainage discharge for different crop fields and ditches and found that controlled drainage may reduce subsurface discharge through field ditches by up to 94%, which is a very attractive option for saving water and reducing water pollution to the Yellow River [20]. Parsons et al. analysed a typical open-ditch drainage system in eastern North Carolina and found that controlled drainage increased the relative yields over conventional drainage and also decreased drainage outflows [21]. Kröger et al. examined the hydrological characteristics of low-grade weirs and found that weir management yielded useful information for non-point source pollutant reduction [22]. Wang et al. studied the influence of a main ditch control project on groundwater in the region and showed that main ditch controlled drainage can ensure crop growth by controlling groundwater [23,24]. Tang et al. studied the impact of different main ditch controlled drainage schemes on the drought and waterlogging of corn and wheat and found that controlling the main ditch water level at a high value can alleviate the effects [25]. Ren et al., through sand tank experiments, studied the effects of different drainage measures and layout forms on farmland drainage and found that compared with subsurface drain drainage, combined drainage with open ditch and subsurface drainage increased drainage by 22.4–32.3% [26]. However, the current researches on controlled drainage mainly focuses on controlled subsurface or field ditch drainage [16] and main ditch controlled drainage [23–25]. There is a lack of research on field ditch controlled drainage and the combined main ditch and field ditch controlled drainage. In particular, the effects of combined main ditch and field ditch control on the crop yield and farmland drainage discharge need be further studied.

China is under the combined influence of East Asian tropical monsoons and East Asian subtropical monsoons; therefore, it is one of the countries with the most serious drought and waterlogging disasters due to the unique natural geography and monsoon climate [27]. The phenomenon of alternating drought and waterlogging occurs in many places in China [28,29], as well as in other parts of the world [30]. From 1950 to 2020, the annual average crop areas influenced by drought and waterlogging were 199.81 thousand hectares and 9.53 billion hectares, respectively [27,31]. The Northern Huaihe River Plain (NHRP) is one of the key grain, cotton, and oil-producing areas in China. Influenced by the monsoon climate and geomorphology, the region has significant spatial variation and interannual variability in rainfall, and drought and waterlogging disasters alternate [32,33]. To effectively reduce waterlogging damage, a large number of open ditches were built from the 1960s to the 1980s, but excessive drainage led to a severe lack of surface water storage. As local crop growth relied mainly on precipitation or groundwater recharge [25], excessive drainage created a serious drought problem [23]. Through years of practice, an effective method to solve this problem was developed in the NHRP, namely, the establishment of an open-ditch controlled drainage system, including main ditches, branch ditches and field ditches (agricultural ditches, side ditches, etc.) and the installation of sluices on the main ditches for control [24]. Wang et al. studied the influence of engineering control measures on the groundwater level in main ditches in farmland in the NHRP [23,24]. Tang et al. studied the effects of different main ditch control levels on drought and waterlogging in farmland [25]. However, at present, there are few studies on field ditch control schemes in the NHRP, and most of them focus on the drainage mode of subsurface drainage pipes and main ditches [26,34].

The NHRP is a typical rain-fed and alternating drought–waterlogging agricultural area. The current main ditch control scheme relies only on experience. For a long time, due to a lack of attention to the application and benefits of agricultural drainage, support for the functioning and maintenance of existing engineering control measures, such as dams and sluices, has been weakened, and old field ditches have been silted and blocked, resulting in the controlled drainage capacity not being properly managed [17]. Therefore, this study uses the existing surface water flow model [35,36], soil water and groundwater movement model [35,37], open ditch water movement model [38–41], and crop growth model [42–44] to develop an open-ditch controlled drainage and crop yield simulation model (ODCDCYSM). By simulating different sluice control schemes for main ditches and layout and outlet weir height control drainage schemes for field ditches, the effect of combined control schemes on crop yield and regional drainage discharge (Q) were evaluated, and then the optimal control scheme was selected to provide a basis for increasing the crop yield, reducing the Q, and achieving sustainable agricultural development and the efficient utilization of agricultural water resources in alternating drought and waterlogging areas.

2. Materials and Methods

2.1. Study Area

The study area is located in the NHRP, Anhui Province, China (33°5′55″–33°18′19″ N, 116°8′17″–116°14′37″ E), mainly in Lixin County (Figure 1a,b). The study area is 22.3 km long from north to south and 7.2 km wide from east to west, with an area of 115.3 km^2, of which approximately 60.5 km^2 is cultivated land. The region is flat and the elevation gradually changes from 31.93 to 27.56 m, with an average gradient of approximately 1:5100. The terrain is high in the northwest and low in the southeast. The study area has a warm temperate subhumid monsoon climate, with significant spatial and interannual variations in rainfall [32,33]. The meteorological data were obtained from the Lixin County meteorological station, which is located in the south of the study area, at 116°10′50″ E, 33°07′12″ N, approximately 1.76 km away from the Chezhe ditch sluice. According to the meteorological data, the annual average precipitation for 1991–2021 was 924 mm, of which approximately 62.3% and 37.7% were concentrated in June–August (rainy season) and September–May (dry season), respectively.

There are five main ditches in the study area, from west to east, namely Xihongsi ditch, Zhonghongsi ditch, Donghongsi ditch, Chezhe ditch and Zhuma ditch. The Zhonghongsi ditch and Donghongsi ditch are located in urban areas and are mainly used for domestic sewage drainage and urban landscaping, with uncontrolled outlets. The Xihongsi ditch, Chezhe ditch and Zhuma ditch run through the study area from north to south; their main function is to collect farm drainage discharge from field ditches, after which they travel southward towards the Fumengxin River and eventually discharge into the Huaihe River (Figure 1b). The southern part of each of the three main ditches is equipped with sluices near the outlet, which are opened to drain during the rainy season and closed in the dry season to raise the groundwater level for crops. However, at present, the Xihongsi ditch and the Zhuma ditch sluices are useless due to disrepair. The Chezhe ditch sluice is the main measure used to control drainage. Based on the field ditch system built in the 1960s to 1980s, the current pattern was gradually formed after years of adjustment to meet the needs of road construction and land development. According to a field investigation and statistical data on Google Maps, the average spacing of the field ditches is 250 m, the depth of the ditches is 1.2 m, and the outlets of the ditches are uncontrolled.

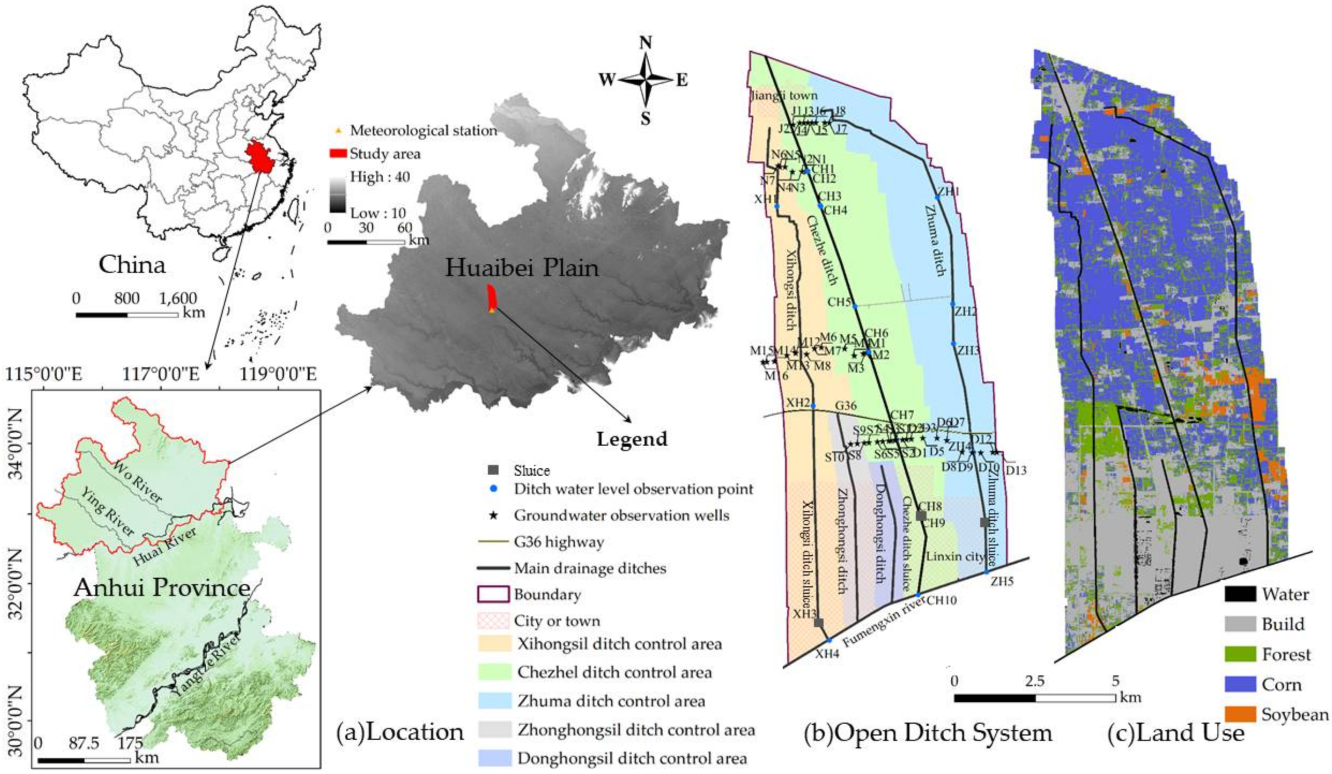


Figure 1. Overview of the study area, where (**a**) shows the location of the study area, the topographic map of Anhui Province was obtained from the National Administration of Surveying, Mapping and Geographic Information of the People's Republic of China (http://www.nasg.gov.cn/ (accessed on 15 May 2022). The DEM source of the NHRP was obtained from the NASA (National Aeronautics and Spacing Administration) website (http://reverb.echo.nasa.gov/reverb/ (accessed on15 May 2022)); (**b**) shows the open ditch system in study area; and (**c**) shows the land use of study area.

The main soil textures of the study area are Shajiang black soil (silty clay) and silt sand. The Shajiang black soil in the upper layer has poor permeability, heavy texture and small soil pores, and it easily becomes dry and hard [45]. The lower layer is brown-yellow silt sand, mainly composed of feldspar quartz, with good permeability. The area is dominated by rain-fed cultivation, food crops in the study area include corn, wheat, soybean, etc., and the planting pattern is mainly a winter wheat–summer corn double cropping system with a wide area. The growing area of crops is shown in Figure 1c (the area planted with wheat is equal to the total area of corn and soybean cultivation).

HOBO water level data loggers (HOBO water level data logger, Onset Computer Corporation, Riverside, CA, USA) were installed in the Chezhe ditch, Xihongsi ditch and Zhuma ditch to record the changes in water level at each section of the ditch (see Figure 1b). To observe the effect of main ditch controlled drainage on regional groundwater, 54 observation wells were placed in five observation lines perpendicular to the direction of flow of the main ditch to monitor the groundwater level change process (see Figure 1b). Among them, 8 wells, Nos. J1–J8, are in the J line, which is about 14.6 km from the Chezhe ditch sluice in the north; 7 wells, Nos. N1–N7, are in the N line, which is about 12.9 km from the Chezhe ditch sluice in the north; 16 wells, Nos. M1–M16, are in the M line, which is about 6.2 km from the Chezhe ditch sluice in north; 10 wells, Nos. S1–S10, are in the S line, which is about 2.8 km from the Chezhe ditch sluice in north; and 13 wells, Nos. D1–D13, are in the D line, which is about 2.8 km from the Chezhe ditch sluice in north.

Crop yield data were mainly obtained from field measurements and the Anhui Statistical Yearbook [46]. From 2019 to 2021, corn in the fields near the groundwater observation wells in the study area was measured, and an average yield of 8110.3 kg/ha was obtained. From 2020 to 2021, wheat in the fields near the groundwater observation wells was measured, and an average yield of 7609.8 kg/ha was obtained. Data for other years were mainly obtained from the Anhui Statistical Yearbook [46].

2.2. Brief Introduction to the ODCDCYSM

Based on the groundwater numerical simulation function of MODFLOW [37], this paper adopts the regional pseudo-three-dimensional soil water groundwater simulation method, regarding the unsaturated zone as a vertical soil column, and uses the one-dimensional Richards equation to solve the soil water movement process [35]. The SCS runoff curve method was used to calculate surface flow production processes for different land-use features [36]. The water balance equation was used to solve the confluence process in branch ditches and field ditches [39]. The Saint-Venant equations were used to solve the confluence process of the main ditch [38]. The soil water, groundwater, ditch drainage discharge and crop yield under different conditions were simulated, and the Erosion/Productivity Impact Calculator (EPIC) model [42] was used to simulate the crop growth and yield. Then, the influence of changing the main ditch water depth, field ditch layout and field ditch outlet weir heights control scheme on the Q and crop yield was simulated. The relationship between various parts of the ODCDCYSM is shown in Figure 2.

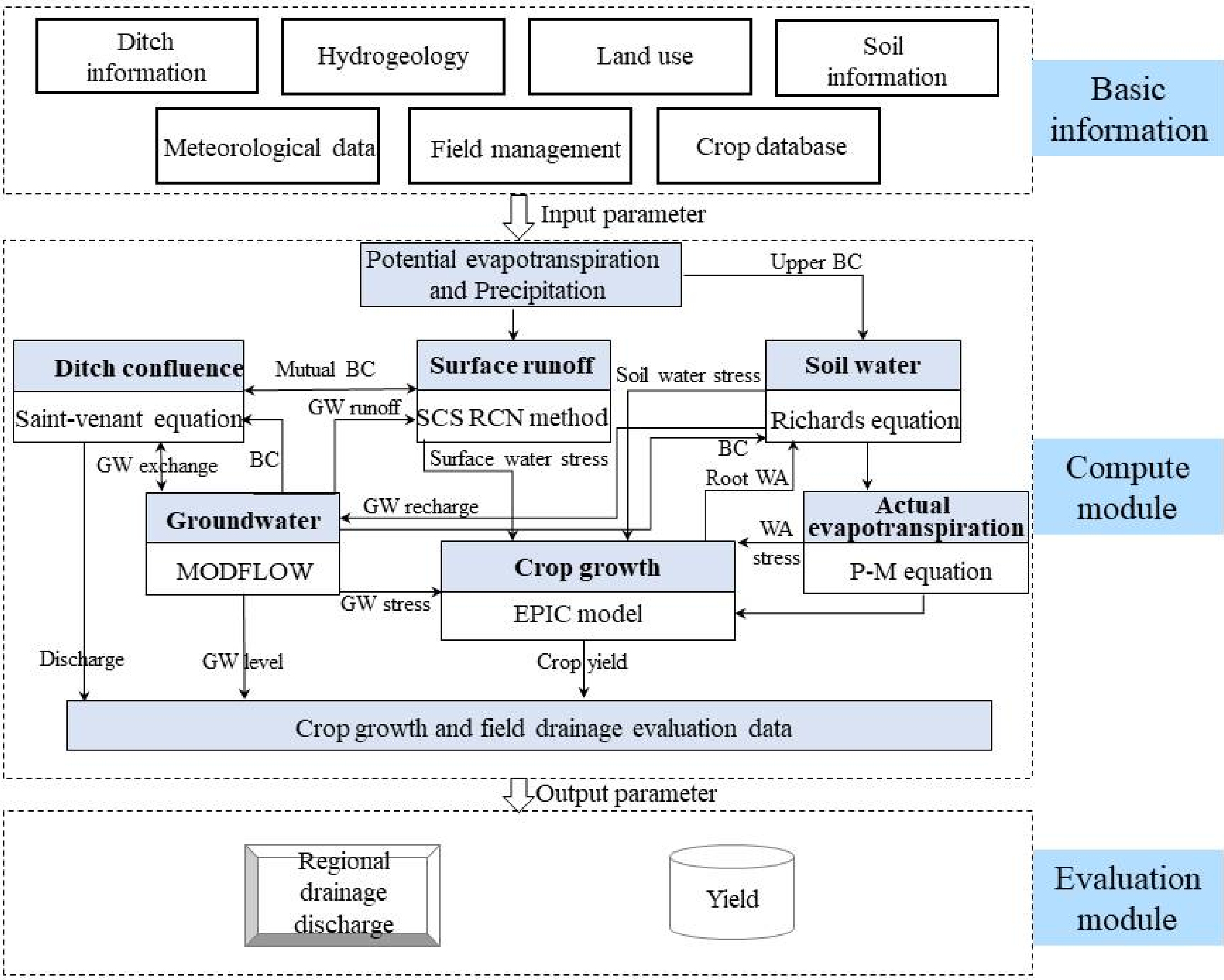


Figure 2. The frame diagram of ODCDCYSM. BC: boundary condition; GW: groundwater; RCN: runoff curve number; WA: water absorption; P–M: Penman–Montes.

2.2.1. Surface Runoff

This paper simulates the surface runoff process according to the runoff characteristics of different land uses. For the farmland with a single underlying surface, the one-dimensional Richards equation (Equation (1)) is used to simulate and solve the soil water movement on the vertical section of the farmland. According to the solution result of Equation (1), the rainfall without infiltration on farmland surface within each time step is regarded as the surface runoff (Q_{surf}), and the equation of surface water balance is Equation (2) [35].

$$\frac{d\theta}{dt} = \frac{\partial}{\partial z}\left(K(h)\frac{\partial h}{\partial z}\right) + \frac{\partial}{\partial z}(K(h)) + S, \tag{1}$$

$$Q_{surrf} = p - F - E, \tag{2}$$

where θ is the volumetric water content [L^3L^{-3}], t is time [T], h is the water pressure head [L], z is the spatial coordinate [L] (positive upward), h is the root water uptake [T^{-1}], and $K(h)$ is the unsaturated hydraulic conductivity [LT^{-1}], Q_{surf} is the flow yield in the time period [L], P is daily precipitation [L], F is the surface infiltration [L], E is surface evaporation [L].

For land-use types such as city, forest, and grassland, the SCS runoff curve method is used to calculate the runoff with the Equation (3) [36]:

$$Q_{surrf} = \begin{cases} \frac{(p-I_a)^2}{(p-I_a+S)} & p \geq I_a \\ 0 & p < I_a \end{cases}, \tag{3}$$

where I_a is the initial abstractions which includes surface storage, interception and infiltration prior to runoff [L], and S is the retention parameter [L].

Rainfall confluence is accomplished through field ditch, branch ditch and main ditch. The water balance equation is used to calculate the drainage volume of field ditch (Equation (4)) [39]. The Hooghoudt equation is used to calculate the exchange capacity between the field ditch and groundwater (Equation (5)) [40,41].

$$\frac{V_{xg,j+1} - V_{xg,j}}{\Delta t_{j+1}} = Q_{xgin} - Q_{xgout} + B_{xg}(P_r - E_w - Q_{g,xg})L_{xg}, \tag{4}$$

$$q = \frac{8kd_e m + 4km^2}{L^2}, \tag{5}$$

where $V_{xg,j+1}$ and $V_{xg,j}$ represent the water volume in the field ditch at time $j+1$ and j respectively [L^3], Q_{xgin} is the total amount of field flow into the field ditch [L^3T^{-1}], Q_{xgout} is the flow from the branch ditch to the main ditch [L^3T^{-1}], P_r and E_w are precipitation rate and evaporation rate respectively [LT^{-1}], B_{xg} is the average water surface width of the field ditch [L], Q_{gxg} is the recharge rate of the field ditch water storage to the groundwater in the current period [LT^{-1}]. q is drainage discharge per unit of drainage area [LT^{-1}], k is the hydraulic conductivity of the soil [LT^{-1}], m is the maximum elevation of the water table above the drains [L], L is the drainage spacing [L], de is the depth of the impermeable layer below the drains [L].

The drainage process of the branch ditch is calculated by the water balance equation (Equation (6)) [39]:

$$\frac{V_{zg,j+1} - V_{zg,j}}{\Delta t_{j+1}} = \sum_{i=1} Q_{zgin,i} - Q_{zgout} + \sum_{o=1} B_{wzg,o}(P_r - E_w - Q_{g,o})\Delta L_o, \tag{6}$$

where $V_{zg,j+1}$ and $V_{zg,j}$ represent the water volume in the branch ditch at time $j+1$ and j, respectively [L^3], Q_{zgin} is the total amount of field ditch into the branch ditch [L^3T^{-1}], Q_{zgout} is the flow from the branch ditch to the main ditch [L^3T^{-1}], B_{wzg} is the average water surface width of the branch ditch [L], Q_g is the recharge rate of the branch ditch water storage to the groundwater in the current period [LT^{-1}]. Subscript i represents the i field ditch of the branch ditch, Subscript m represents the m section of the branch ditch, and ΔL_m is the length of the branch ditch in segment m [L].

The confluence and drainage process of the main ditch is calculated by using Saint-Venant's equations (Equation (7)) [38]:

$$\begin{cases} \frac{\partial Q}{\partial s} + B\frac{\partial H}{\partial t} = q \\ \frac{\partial Q}{\partial t} + \frac{\partial}{\partial s}(\alpha\frac{Q^2}{A}) + gA\frac{\partial H}{\partial s} + gAS_f = qv_s \end{cases}, \tag{7}$$

where Q is the discharge in main ditch [L^3/T], s is the distance in the direction of movement of the water [L], B is the water surface width of the ditch [L], H is the ditch water level [L], A is the area of the overwater section [L^2], q is the net lateral discharge into the ditch [L^2T^{-1}], α is the flow correction coefficient; g is the acceleration of gravity [LT^{-2}], v_s is the velocity of q along the direction of the flow [LT^{-1}], Sf is the gradient of friction resistance.

Referring to the river boundary and drain boundary in MODFLOW 2005 [37], the exchange volume between ditch water and groundwater in branch ditch and main ditch is calculated as follows:

(1) When there is water flow in the ditch:

$$Q_{dw} = C_d(Z_d - Z_w), \tag{8}$$

where Q_{dw} is the discharge of the main and branch ditch into the field ditch [L^3T^{-1}], C_d is the hydraulic conductivity of soil between ditch and groundwater [L^2T^{-1}], Z_d and Z_w are ditch water level and groundwater level, respectively [L].

(2) When the ditch dries up:

$$Q_{dw} = \begin{cases} C_d(Z_{dbot} - Z_w) & Z_{dbot} \le Z_w \\ 0 & Z_{dbot} > Z_w \end{cases}, \tag{9}$$

where Z_{dbot} is the ditch bottom elevation [L].

2.2.2. Groundwater Movement

The MODFLOW numerical model based on finite difference method is used to calculate the regional groundwater movement. The governing equation of the model is shown in Equation (10) [37]:

$$\frac{\partial}{\partial x_i}\left(K_{ij}\frac{\partial H}{\partial x_j}\right) + W = S_S\frac{\partial H}{\partial t}, \tag{10}$$

where i, j = 1–3, represent the x, y and z directions, respectively; K_{ij} denotes the saturation hydraulic conductivity tensor [LT^{-1}], H is the pressure head [L], W is the flux of source/sink per unit volume [L^3T^{-1}], S_S is the specific yield of the porous medium; and t denotes time [T].

2.2.3. Evapotranspiration

The Penman–Montes equation (Equation (11)) recommended by FAO-56 [47] based on the principles of energy balance and aerodynamics is used to calculate the daily potential evapotranspiration ET_p of crops.

$$\lambda ET_p = \frac{\Delta(R_n - G) + \rho_a c_p(e_s - e_a)/r_a}{\Delta + \gamma(1 + r_s/r_a)}, \tag{11}$$

where ET_0 is the evapotranspiration rate, [LT^{-1}]; λ is the psychrometric constant [L^2T^{-2}], R_n is net radiation [MT^{-3}], G is the soil heat flux [MT^{-3}], ρ_a is the mean air density at constant pressure, [ML^{-3}]; c_p is the specific heat of the air; $(e_s - e_a)$ is the vapor pressure deficit [$ML^{-1}T^{-2}$]; r_s is the surface resistance [TL^{-1}], and r_a is the aerodynamic resistance [TL^{-1}].

When crops are present on the ground, ET_p is calculated and then separated into E_p (potential evaporation) and T_p (potential transpiration) based on the LAI of the crops, calculated in Equations (12) and (13) below. For each field, the calculated E_p and T_p are added into Richards equation to calculate the actual evapotranspiration and soil water movement for the day.

$$T_p = (1 - \exp(-fLAI))ET_p, \tag{12}$$

$$E_p = ET_p - T_p, \tag{13}$$

where *f* is the light extinction coefficient, *LAI* is the leaf area index of crops.

2.2.4. Crop Growth Model

The EPIC model is used to simulate the growth and yield formation process of crops; the model mainly includes five parts: the potential biomass growth, water use, nutrient absorption, growth stress, and crop yield [42,43]. Crop model parameters are driven by meteorological data, and daily heat unit accumulation is used to calculate daily crop biomass accumulation, root growth, height and *LAI*. The Beer's law equation is used to calculate interception of solar radiation. The *LAI* is estimated as a function of heat units, crop stress, and crop developmental stage. The intensity of stress factors is used to estimate the influence degree of stress factors such as soil resistance, temperature and water on the root system, and the actual daily growth of the crop is calculated by taking day as the time step. According to the actual daily growth of the crop, a part of the new growth is added to determine the water absorption of the root system of the crop. The rest is allocated to the above-ground part (the above-ground biomass). Finally, the accumulated above-ground biomass is used to calculate crop yield through the harvest index (Equation (14)) [42,44].

$$yld = HI \cdot Ba, \tag{14}$$

where *yld* is the simulated crop yield [ML^{-2}], *HI* is the harvest index; *Ba* is the weight of accumulated above ground biomass [ML^{-2}].

2.3. Crop yield and Regional Drainage Discharge

Efforts are ongoing to make full use of rainfall resources, reduce nitrogen, salt, and other chemicals entering the river with farmland drainage discharge and reduce farmland non-point source pollution on the premise of ensuring crop yield; research shows that the total amount of nitrogen and other chemicals excluded from farmland mainly depends on the total water volume of farmland drainage [34,48]. Therefore, this paper selects the following two indicators to evaluate the regional open ditch control drainage system. The first indicator is the crop yield. The crop yield of each simulation unit is calculated based on the EPIC model, and the per-unit yield of corn and wheat are obtained from the area-weighted average. The second indicator is the regional drainage discharge (Q), which is the daily average of the sum of the discharge of the five main ditch outlets.

2.4. Scenario Simulation Settings

2.4.1. Single-Factor Main Ditch Water Depth Control Schemes

Different main-ditch water-depth control scenarios were set in the dry season and rainy season according to the local rainfall characteristics and the actual operation of the main ditch (scenario 1 in Table 1). Based on the actual main ditch control rules and the possible sluice control scheme, the sluice control schemes of the Chezhe ditch, Xihongsi ditch and Zhuma ditch were set in steps of 0.5 m, with a total of 16 schemes (Table 1). The field ditch remained unchanged and represented the current situation (i.e., the drainage spacing was 250 m, drainage depth was 1.2 m, and the ratio of weir height to drainage depth was 0).

Table 1. Single-factor main ditch water depth control schemes.

Scenario Number	WD in Dry Season (m)			WD in Rainy Season (m)		
	WD Number	Open Sluices	Close Sluices	WD Number	Open Sluices	Close Sluices
1	A	Always close (5)		D	4	3
2	B	5	4	B	5	4
3				C	4.5	3.5
4				D	4	3
5				E	3.5	2.5
6				F	3	2
7	C	4.5	3.5	C	4.5	3.5
8				D	4	3
9				E	3.5	2.5
10				F	3	2
11	D	4	3	D	4	3
12				E	3.5	2.5
13				F	3	2
14	E	3.5	2.5	E	3.5	2.5
15				F	3	2
16	F	3	2	F	3	2

Note: WD is water depth. The dry season refers to September to May of the following year, and the rainy season refers to June to August. The data in the "Open Sluices" column indicate the minimum ditch water depth when opening the sluice, for example, "4" means opening the sluice when the water surface is 4 m or more away from the ditch bottom; the data in the "Close Sluices" column indicates the maximum ditch water depth when the gate is closed. For example, "3" indicates that the gate is closed when the water surface is less than or equal to 3 m from the ditch bottom.

2.4.2. Single-Factor Field Ditch Schemes

To study the effects of different field ditch layouts and control schemes on crop yield and Q, 3 drainage spacings (100 m, 250 m, 400 m), 3 drainage depths (0.8 m, 1.2 m, 1.6 m) and 3 ditch outlet control drainage schemes (ratio of weir height to drainage depth: 0, 1/2, 1) were set, which were combined into 27 scenarios. Main-ditch water-depth control represented the current situation (scenario 1 in Table 1) and remained unchanged. The current field ditch situation was scenario 13 in Table 2.

Table 2. Single-factor field ditch schemes.

Drainage Spacings (m)	Drainage Depths (m)	Ratio of Weir Height to Drainage Depth		
		0	0.5	1
		Scenario Number		
100	0.8	1	2	3
	1.2	4	5	6
	1.6	7	8	9
250	0.8	10	11	12
	1.2	13	14	15
	1.6	16	17	18
400	0.8	19	20	21
	1.2	22	23	24
	1.6	25	26	27

2.4.3. Combined Control Scheme Settings

First, from among the single-factor main ditch schemes and field ditch schemes, four main ditch schemes (M1–M4; scenarios 5, 9, 12 and 14 in Table 1) and three field ditch schemes (F1–F3; scenarios 17, 23 and 26 in Table 2), which were better than the current situation (M0F0; scenario 1 in Table 1 and scenario 13 in Table 2), were selected for combined control. There were 12 combined control schemes, as shown in Table 3.

Table 3. Combined main ditch and field ditch control schemes.

Scenario Number	Ditch Plan	Main Ditch Control Schemes				Field Ditch Control Schemes		
		WD in Dry Season (m)		WD in Rainy Season (m)		Drainage Spacings (m)	Drainage Depths (m)	Ratio of Weir Height
		Open Sluices	Close Sluices	Open Sluices	Close Sluices			
0	M0F0	5	5	4	3	250	1.2	0
1	M1F1	5	4	4.5	3.5	250	1.6	0.5
2	M1F2					400	1.2	0.5
3	M1F3					400	1.6	0.5
4	M2F1	4.5	3.5	3.5	2.5	250	1.6	0.5
5	M2F2					400	1.2	0.5
6	M2F3					400	1.6	0.5
7	M3F1	4	3	3.5	2.5	250	1.6	0.5
8	M3F2					400	1.2	0.5
9	M3F3					400	1.6	0.5
10	M4F1	3.5	2.5	3	2	250	1.6	0.5
11	M4F2					400	1.2	0.5
12	M4F3					400	1.6	0.5

3. Results and Discussion

3.1. Model Calibration and Validation

The observed main ditch water level, groundwater level and crop yield were used for calibration and validation of the model, including the main ditch water level of a typical section (the M Line to Chezhe ditch sluice), the groundwater level of 54 observation wells at the observation lines (J, N, M, D and S lines, Figure 1b), and measured crop yields from 2017 to 2021. The model calibration period was 882 days from 1 January 2017 to 1 June 2019. The model validation period was 731 days from 2 June 2019 to 1 June 2021. The coefficient of determination (R^2), standardized root mean square error (*NRMSE*), root mean square error (*RMSE*), and the relative error (*RE*) were selected as indexes to evaluate the simulation results [49–52]. The calculation equation of each index can be seen Supplementary material (Equations (S1)–(S3)).

The surface runoff module mainly used the SCS runoff curve method, and the CN values were shown in Table S1. The soil hydraulic parameters were calibrated according to the initial values of the measured data. Table S3 shows the values of the soil hydraulic parameters in the Van Genuchten–Mualem formula [35]. Parameters such as the soil permeability coefficient (k) and roughness (n) at the bottom of the main ditch, according to the water level of the main ditch in the ditch confluence module, were calibrated. The calibration results are shown in Table S2. The groundwater module was mainly calibrated for the hydraulic conductivity and specific yield, and the results are shown in Table S3. The data from EPIC's Crop Parameters Database in the USA were used as the initial values of the crop parameters in the model [42], which were adjusted according to the crop yield (see Table S4). In Huang-Huai-Hai Plain, the hydraulic conductivity of silty clay was 1–4.7 m/d, the hydraulic conductivity of silt sand was 5–17 m/d, the specific yield of silty clay is 0.03–0.06, the specific yield of silt sand was 0.09–0.17 m/d [53], and the soil permeability coefficient at the bottom of the ditch was 0.01–2.93 m/d [54,55]. The ccalibrated hydraulic conductivity, specific yield and soil permeability coefficient at the bottom of the ditch were within the above range.

3.1.1. Main Ditch Water Level

In the calibration and validation period, according to the calculated main ditch water level of the typical section (the M Line to Chezhe ditch sluice), the R^2 values were 0.57 and 0.68, respectively; the *NRMSEs* and *REs* were all 0 m; the *RMSEs* were 0.23 and

0.27 m, respectively; the *REs* were all 0 m (Figure 3a,b). Figure 3c,d shows the comparison of simulated and observed water level during the calibration and validation period, respectively. The simulated values were basically the same as the observed values and the ditch water level changes drastically during the opening of the sluices, resulting in the difference between simulated value and measured value being relatively large.

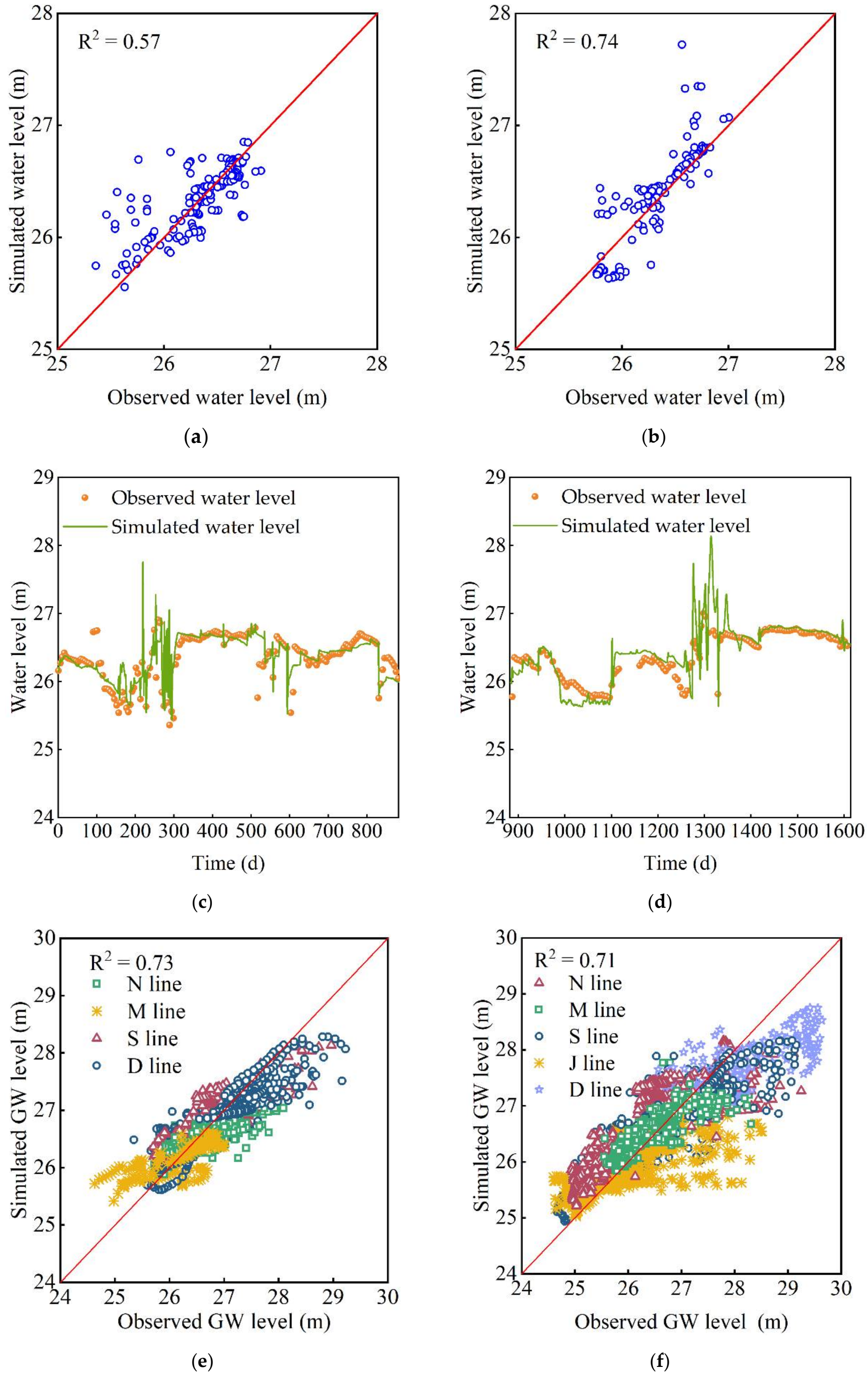


Figure 3. Simulation of groundwater level and main ditch water level in the study area during calibration period and validation period. Comparison of the main ditch levels during the calibration period (**a**) and the validation period (**b**). Comparison of measured and simulated water level in main ditch during the calibration period (**c**) and the validation period (**d**). Comparison of the groundwater levels during the calibration period (**e**) and the validation period (**f**).

3.1.2. Groundwater Level

In the calibration and validation period, according to the calculated groundwater level from all groundwater level observation wells at Lines J, N, M, S and D in the study area, the *NRMSEs* were 1.1% and 1.8%, respectively; the *RMSEs* were 0.31 and 0.48 m, respectively; the R*Es* were all 0.00 m; and the R^2 values were all above 0.71 (Figure 3e,f). The *NRMSEs* were less than 0.25, REs were less than 0.2, and R^2 values were greater than 0.65, indicating that the groundwater level simulation results were reliable [49].

3.1.3. Crop Yield

Table S5 shows the comparison between simulated and measured values of annual average corn and wheat yields in the study area from 2017 to 2021. The yield of the two crops was simulated well. The *NRMSE*, *RMSE* and *RE* of summer corn were 1.3%, 105.1 kg/ha and −0.0071 kg/ha, respectively. The *NRMSE*, *RMSE* and *RE* of winter wheat were 1.2%, 84.9 kg/ha and 0.0001 kg/ha, respectively. This indicated that the yield simulation results of corn and wheat were reasonable and reliable.

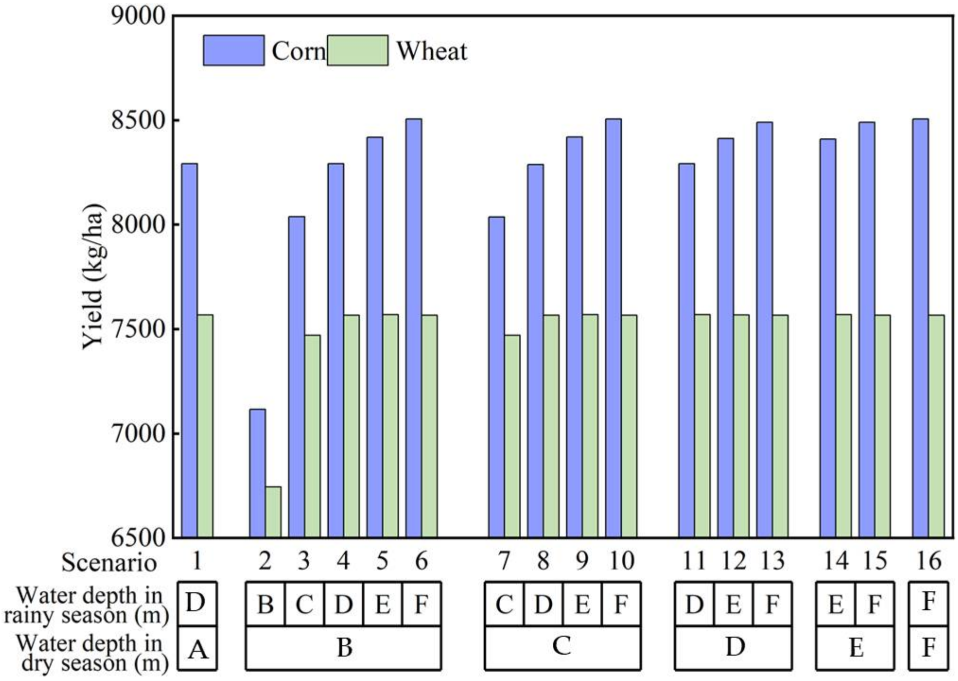
3.2. Effects of Single-Factor Main Ditch and Field Ditch Control Schemes on Crop Yield and Q

To study the effects of main ditch sluice control schemes and field ditch layouts and control schemes on the crop yield and Q and to explore feasible drainage management measures for the NHRP, different main ditch and field ditch scenarios were set. Based on meteorological data from the 30 years from 1991 to 2021, the above models were used to simulate the changes in crop yield and Q. The effects of the open ditch control drainage system on crop yield and Q were analysed, and the optimal scenarios were selected to achieve the dual goals of ensuring crop yield and reducing farmland drainage discharge and to provide technical support for increasing food production and reducing Q.

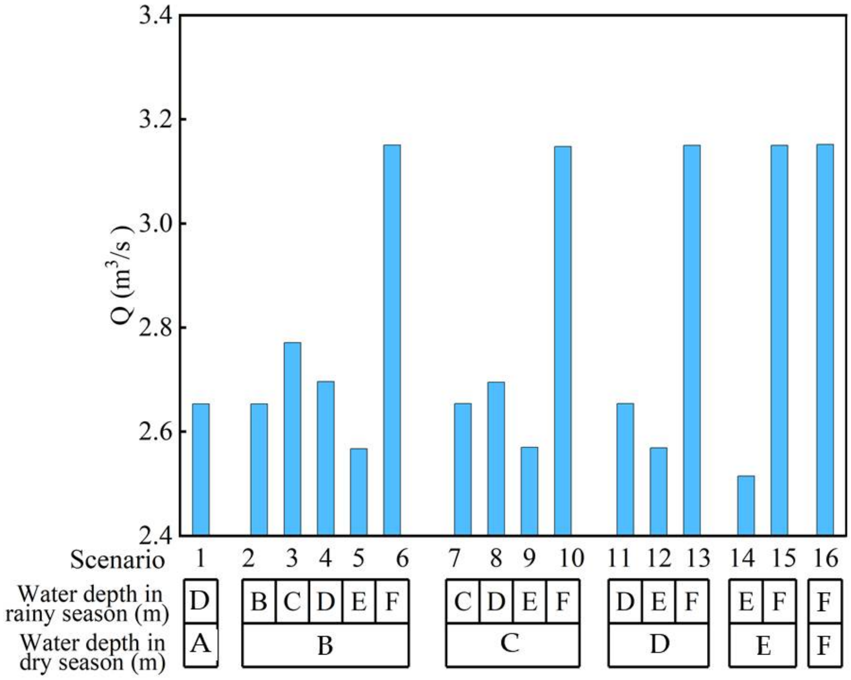
3.2.1. Effects of Single-Factor Main Ditch Water Depth Control on Crop Yield and Q

(1) Effects of Single-Factor Main Ditch Water Depth Control on Crop Yield

Figure 4 shows the changes in the average annual corn and wheat yield and Q from 1991 to 2021 under the different main ditch water depth control schemes. In scenarios with the same uppermost and downmost limits of main ditch water depth (UDLMDWD) in the dry season (taking B as an example, corresponding to scenarios 2–6), the corn yield increased with the decrease in UDLMDWD in the rainy season. The corn yield reached the maximum in scenario 6, increasing by 2.5% compared with the current scenario (scenario 1). This result shows that the UDLMDWD should not be too high in the rainy season. When it is too high, the water in the field cannot be discharged in time, the corn may be under waterlogging stress, and the corn yield will decrease [13]. As demonstrated by Jouni et al. and Wayne Skaggs et al. [14,16], controlled drainage had a positive impact on the corn yield. The wheat yield first increased and then decreased with the decrease in UDLMDWD, and the wheat yield reached the maximum in scenario 5. The UDLMDWD for wheat in the rainy season was higher than that for corn. The average annual rainfall in the dry season in the study area was 349.8 mm, which was far lower than the water requirement range (450–650 mm) of wheat [56]. Therefore, more water needs to be stored during the rainy season to meet the demand of wheat growth. In the case of the same UDLMDWD in the rainy season (taking F as an example, corresponding to scenarios 6,10,13,15 and 16). With the decrease in UDLMDWD in the dry season, the corn and wheat yields did not change much and were approximately 8499 kg/ha and 7566 kg/ha, respectively. Due to the uneven distribution of local rainfall throughout the year, most of the heavy rain occurred in the rainy season [32], and the control of the main ditch in the dry season had little impact on crops.



(**a**)



(**b**)

Figure 4. Changes in evaluation indexes under different main ditch water depth control schemes. (**a**) Crop yield; (**b**) regional drainage discharge (Q).

The corn and wheat yields were both the lowest in scenario 2. The UDLMDWD values in the rainy season and dry season were both relatively high; the yield of corn was reduced by 1176.6 kg/ha and the yield of wheat was reduced by 822.8 kg/ha. The corn yields were highest for corn in scenario 16 (8505.5 kg/ha) and highest for wheat in scenario 14 (7569.2 kg/ha), with wheat requiring a higher UDLMDWD than corn. The aim was to increase the crop yield as much as possible, and compared with the current situation, the yield was increased through the single-factor main ditch control schemes, as show in Table S6. The scenarios that increased the yield of both crops at the same time were scenarios 5, 9, 12 and 14.

(2) Effects of Single-Factor Main Ditch Water Depth Control on Q

According to Figure 4b, in the case of the same UDLMDWD in the dry season (taking B as an example, corresponding to scenarios 2–6), Q showed a trend of first increasing, then decreasing and then increasing with the decrease in UDLMDWD in the rainy season. This indicated that in schemes D and E, the interaction between the main ditch and groundwater was strong, and most of the ditch water was supplied to the groundwater. In scenario 5, the minimum Q was reached (2.6 m^3/s), which was 3.2% less than the current situation (scenario 1). In the case of the same UDLMDWD in the rainy season (taking F as an example, corresponding to scenarios 6, 10, 13, 15 and 16). With the decrease in UDLMDWD in the dry season, Q showed a trend of first decreasing and then increasing, but the change was not large, and the difference between the maximum and minimum values was only 0.004 m^3/s. The results show that UDLMDWD in the dry season had little effect on Q, which may be related to the low rainfall in the dry season.

The minimum Q in scenario 14 was 2.51 m^3/s, which was 5.2% lower than that of the current scenario. The Q values of scenarios 6, 10, 13, 15 and 16 were large, reaching 3.15 m^3/s in scheme (F) with the UDLMDWD in the rainy season, increasing by approximately 18.7% compared with the current scenario. Q decreased only through the control of the main ditch, as shown in Table S6.

From the dual perspective of improving the rainfall utilization and reducing farmland drainage discharge to reduce farmland non-point source pollution, scenario 14 was the best scheme that satisfied both crop yield increases and Q reductions among the single-factor main ditch control schemes, followed by scenarios 5, 9 and 12.

3.2.2. Effects of Single-Factor Field Ditch Control Schemes on Crop Yield and Q

(1) Effect of Drainage Spacings of Field Ditches

Figure 5a,b show the changes in corn and wheat yields and Q in the study area under the condition of only considering changes in field ditch drainage spacings. The drainage spacings were 100 m, 250 m and 400 m, the drainage depth was 1.2 m, and the ratio of weir height to drainage depth was 0 (free drainage). According to Figure 5a, as the drainage spacing increased, the corn yield increased accordingly, and the maximum corn yield was obtained when the drainage spacing was 400 m. The local area mainly relied on water lifting for irrigation, so the cost is high, and local food crops are only rain-fed and are in a state of drought most of the time, resulting in higher crop yields in scenarios with a large drainage spacing and poor drainage conditions. The wheat yield first increased and then decreased as the drainage spacing increased, and the maximum wheat yield was obtained when the drainage spacing was 250 m, mainly because when the drainage spacing was small, the rainwater drained away in time, and when there was no rain for many days, the area easily suffered from drought. When the drainage spacing became larger, the drainage conditions in the field were poor, and the crops were susceptible to waterlogging when the rainfall intensity was high or rainfall was continuous for several days. Under drought conditions, a larger drainage spacing reduces drainage discharge, thus reducing potential drought stress, which can be beneficial in improving crop yields. In wet conditions, the smaller drainage spacing removes excess water in time, thus reducing waterlogging and increasing crop yields. The results were consistent with the results of Acharya et al. [57] as well as Ghane and Askar [58] regarding the effect of spacing between subsurface drainage pipes on the crop yield.

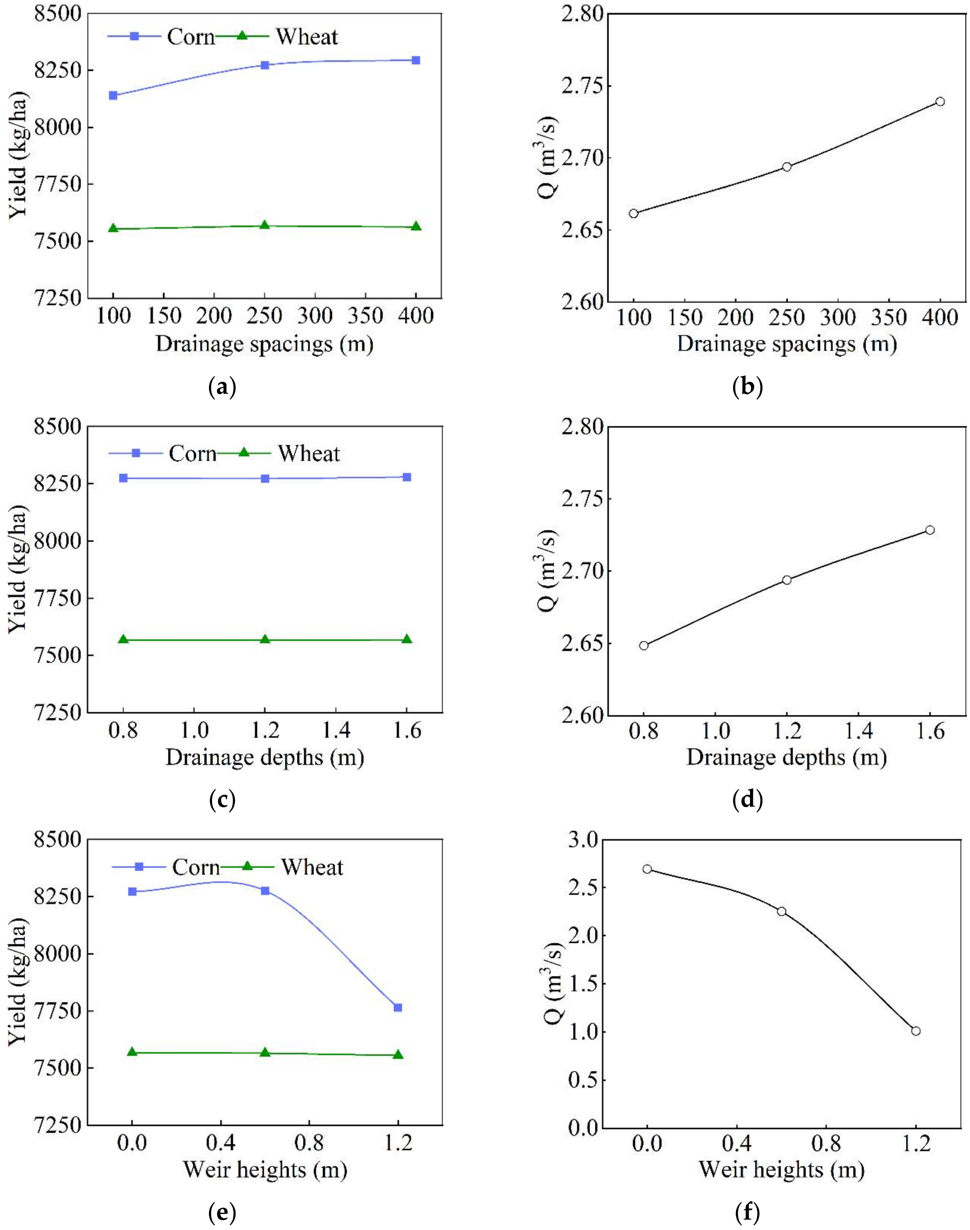


Figure 5. Changes in crop yield and Q under the effect of different field ditch control schemes. (**a**,**b**) Drainage spacing; (**c**,**d**) drainage depth; (**e**,**f**) weir height.

Figure 5b shows the change in Q with different field ditch drainage spacings. When the drainage spacing was increased, the Q increased. This was mainly because when the drainage spacing became larger, the number of small ditches decreased, and the recharge of groundwater through field ditches in surface water decreased, resulting in an overall increase in surface drainage discharge.

(2) Effect of Field Ditch Drainage Depth

Figure 5c,d show the changes in corn and wheat yields and Q in the study area under the condition of only considering changes in the drainage depth of the field ditch. The drainage spacing was 250 m, drainage depths were 0.8 m, 1.2 m and 1.8 m, and the ratio of weir height to drainage depth was 0 (free drainage). According to Figure 5c, the drainage depth increased, the corn yield first decreased and then increased, and the wheat yield increased, reaching the maximum when the drainage depth was 1.6 m. Compared with the current situation (drainage depth of 1.2 m), the yield of the two crops did not change much, which indicated that field ditch drainage depths between 0.8 and 1.6 m had little effect on crop yield.

Figure 5b shows the change in Q with different field ditch drainage depths. With an increase in the drainage depth, the Q increased. This was mainly because the bottom elevation of the field ditch became lower. When the groundwater level and ditch depth were the same, the difference in water level between the ditch and groundwater level decreased, and the recharge rate and amount from the ditch to the groundwater decreased. The results were consistent with the results of Muhammad et al. [59] regarding the effect of depth between subsurface drainage pipes on Q.

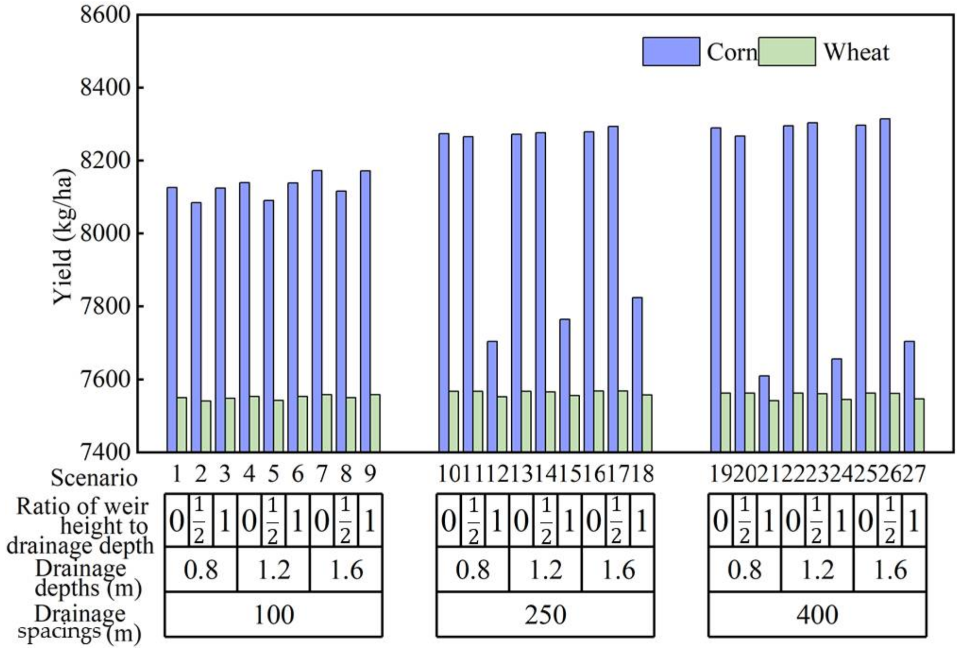
(3) Effect of Field Ditch Weir Height

Figure 5e,f show the changes in corn and wheat yields and Q in the study area under the condition of only considering changes in the ratio of weir height to drainage depth. The drainage spacing of the field ditches was 250 m, the drainage depth was 1.2 m, and the ratio of weir height to drainage depth was 0, 1/2 and 1, corresponding to weir heights of 0 m, 0.6 m and 1.2 m, respectively. According to Figure 5e, the weir height increased, and the corn yield first increased then decreased, and reached the maximum when the weir height was 0.6 m. The wheat yield decreased, and the wheat yield was the largest when the weir height was 0 m. When the weir height was 1.2 m, compared with the current situation, corn and wheat yield were reduced by 567.7 kg/ha and 15.2 kg/ha, respectively. Therefore, field ditches should be kept free draining to make the crop as productive as possible. With an increase in the weir height, the drainage capacity of the ditch decreased, the amount of water retained in the field ditch increased, and the Q decreased continuously.

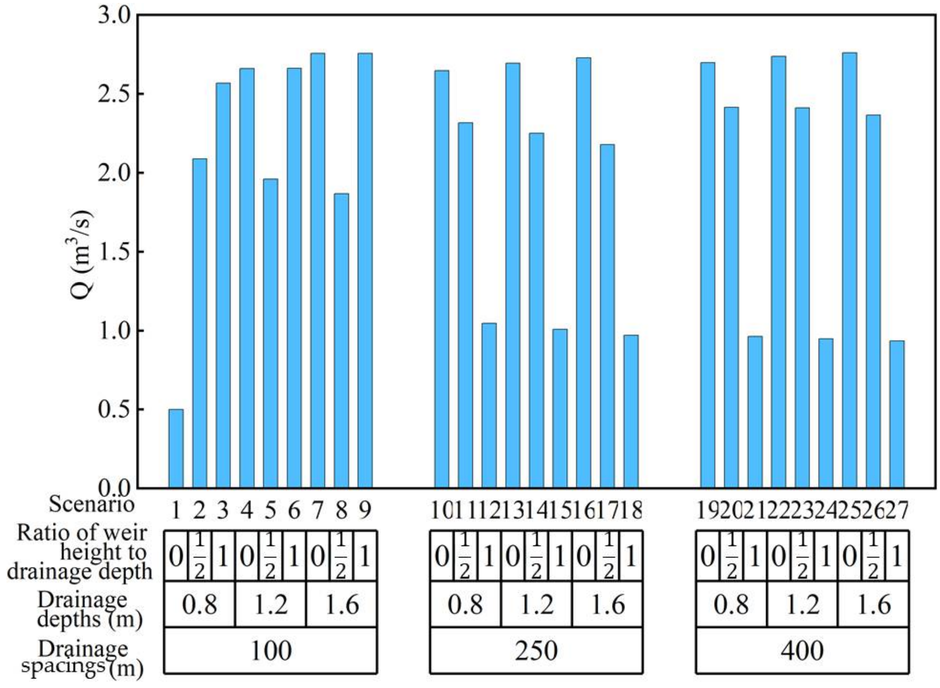
Compared with the current situation, the changes in corn yield, wheat yield and Q caused by changes in field ditch drainage spacings change were 155.8 kg/ha, 9.7 kg/ha and 0.08 m^3/s, respectively. The changes in the corn yield, wheat yield and Q caused by the change in drainage depths in field ditches were 5.1 kg/ha, 1.2 kg/ha and 0.08 m^3/s, respectively. The changes in corn yield, wheat yield and Q caused by changes in the field ditch weir heights were 511.2 kg/ha, 19.9 kg/ha and 1.24 m^3/s, respectively. In conclusion, the variation in crop yield and Q were significantly influenced by the weir height, followed by the drainage spacing and depth.

(4) Optimal Scenario Analysis of Single-Factor Field Ditch Schemes

Figure 6 shows the change in average annual yield of corn and wheat and Q from 1991–2021 for all the different combinations of scenarios considering three factors: field ditch drainage spacing, drainage depth and ratio of weir height to drainage depth. Figure 6a shows that among the different field ditch schemes, the corn yield reached the maximum in scenario 26, and compared with the current situation scenario (scenario 13), the yield increase rate was 0.05%. The corn yield reached the minimum in scenario 21, and scenarios 12, 15, 18, 24 and 27 were almost similar to scenario 21, with a corn yield of approximately 7687 kg/ha when the field ditch weir height was 1.2 m. Compared with the current situation (Scenario 13), the corn yield reduction rate was 5.4–8.1%. The maximum wheat yield was obtained under scenario 16, and the minimum was obtained under scenario 2, with a non-significant wheat yield variation of approximately 27.6 kg/ha, indicating that field ditch control had little effect on the wheat yield. The crop yield improvements obtained with field ditch control measures compared with the current scenario are shown in Table S7. In summary, the scenarios that simultaneously achieved crop yield increases in the two crops were scenarios 16 and 17.



(**a**)



(**b**)

Figure 6. Changes in evaluation indexes under different field ditch water depth control scheme. (**a**) Crop yield; (**b**) regional drainage discharge (Q).

According to Figure 6b, the Q values of scenarios 7, 9, 16, 22 and 25 were relatively large, reaching 3.7 m^3/s, and the weir height was 0 m. Compared with the current situation, the increase range of the Q was 1.3–2.5%. The Q values of scenarios 12, 15, 18, 21 and 24 were relatively small, where Q was reduced by more than 60% from the current situation scenario, and the weir height was 1.2 m. Through field ditch control measures, the Q decreased compared with the current scenario, as shown in Table S7.

Since changing field ditch control measures had no significant effect on the wheat yield, the results considering only the corn yield and Q showed that scenario 26 was the best scenario to achieve an increase in crop yield and decrease in Q under the single-factor field ditch control schemes, followed by scenarios 23 and 17.

3.3. Effects of Combined Control Schemes for Main Ditch and Field Ditch on Crop Yield and Q

In the process of field runoff and crop growth, changes in the crop yield and Q are the result of the combined action of multiple factors. The interaction of multiple factors may enhance (or weaken) the influence of a single factor on the crop yield and Q and enhance (or weaken) the degree of drought and waterlogging. Therefore, it was important to reveal that the combined control of the main ditch and field ditch had an important effect on the crop yield and Q.

An optimal open-ditch controlled drainage system was established to effectively reduce the loss of crops after drought and waterlogging disasters and the water environment pollution caused by farmland drainage discharge. From the single-factor main ditch and field ditch schemes, the schemes that could increase the crop yield and reduce the Q were selected for combined control, the changes in crop yield and Q under combined control were analysed, and the optimal combined control scheme was obtained.

3.3.1. Effects of Combined Control Schemes on Crop Yield

Table 4 compares the crop yield under the combined control schemes and the current situation. Compared with the current situation (M0F0), the corn and wheat yields increased with mean values of 156.7 kg/ha and 1.6 kg/ha, respectively. The maximum yield increase for corn occurred in M4F3 (166.7 kg/ha) and the maximum yield increase for wheat occurred in M4F2 (2.4 kg/ha). These two schemes had the same main ditch control scheme M4 (opening and closing the sluice at 3 m and 2 m in the rainy season, and at 3.5 m and 2.5 m in the dry season).

Table 4. Comparison of crop yield and regional drainage discharge with the current situation under the combined control schemes.

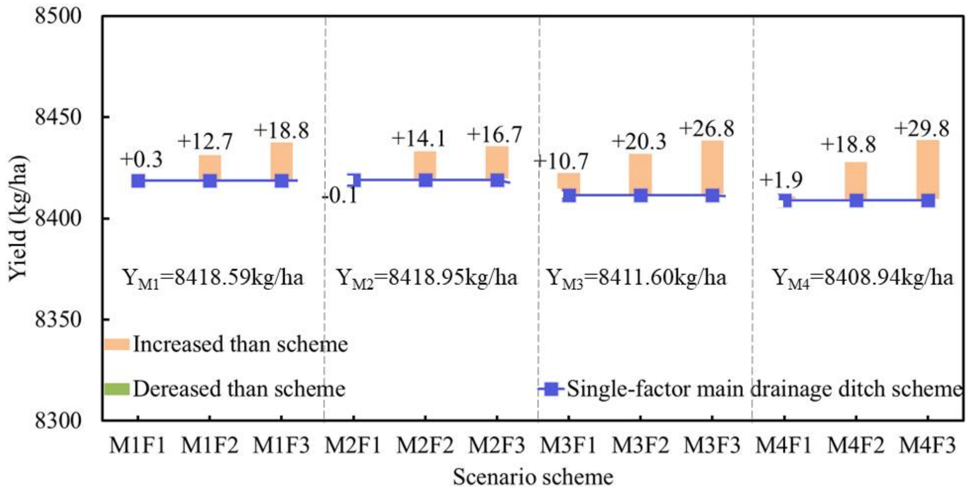
Scenario Number	Ditch Plan	Corn		Wheat		Regional Drainage Discharge	
		Yield (kg/ha)	Increased Yield (kg/ha)	Yield (kg/ha)	Increased Yield (kg/ha)	Q (m^3/s)	Emission Reduction (m^3/s)
0	M0F0	8272.1	—	7567.2	—	2.69	—
1	M1F1	8418.9	146.8	7568.4	1.2	2.10	0.60
2	M1F2	8431.3	159.2	7568.7	1.5	2.33	0.36
3	M1F3	8437.4	165.3	7567.7	0.5	2.28	0.41
4	M2F1	8418.9	146.8	7568.9	1.7	2.10	0.60
5	M2F2	8433.1	161.0	7568.9	1.7	2.34	0.36
6	M2F3	8435.7	163.6	7568.5	1.4	2.28	0.41
7	M3F1	8422.3	150.3	7569.2	2.0	2.10	0.60
8	M3F2	8431.9	159.8	7569.0	1.8	2.33	0.36
9	M3F3	8438.4	166.4	7568.1	0.9	2.28	0.41
10	M4F1	8410.9	138.8	7568.8	1.6	2.05	0.64
11	M4F2	8427.7	155.6	7569.6	2.4	2.29	0.40
12	M4F3	8438.7	166.7	7569.0	1.8	2.24	0.45

Note: Those in red in the table indicate that the five scenarios with yields of the two crops and regional drainage were better than the current scenario.

Figure 7a,b compare the crop yields under the combined control schemes and the single-factor main ditch schemes (M, the field ditch control scheme reflected the current situation). Compared with the single-factor main ditch schemes, with the field ditch control, the corn yield increased overall, except for a slight decrease in the M2F1 scenario (yield reduction of 0.1 kg/ha). The scenario with the maximum yield increase in corn was M4F3, and the scenarios with higher corn yield increases were a combination of main ditch control schemes (M1–M4) and field ditch control scheme F3 (drainage spacing 400 m, drainage depth 1.2 m, ratio of weir height to drainage depth 1/2), which showed that this field ditch scheme was suitable for the growth of corn. The overall variation in wheat yields was small, and the range was approximately 0–1.2 kg/ha, with the maximum wheat yield increase occurring in M3F1. The scenarios with a higher wheat yield increase were a combination of main ditch control schemes (M1–M4) and field ditch control scheme F2 (drainage spacing 400 m, drainage depth 1.2 m, ratio of weir height to drainage depth 1/2), which shows that this field ditch scheme was suitable for the growth of wheat. In general, the drainage depth of field ditches had a certain impact on the crop yield, but it was not significant. By comparison, for field ditch control schemes F3 and F2, the drainage depth in the dry season of the wheat growing period was lower than that in the rainy season of the corn growing period, and the drainage capacity of wheat was weaker than that of corn. Ghane et al. [58] compared the corn yield in deep and shallow ditches in the eastern United States and found that the corn yield in shallow ditches increased in dry years and decreased in wet years, which indicates that the corn yield is related to soil characteristics, dry and wet weather, and field ditch specifications.

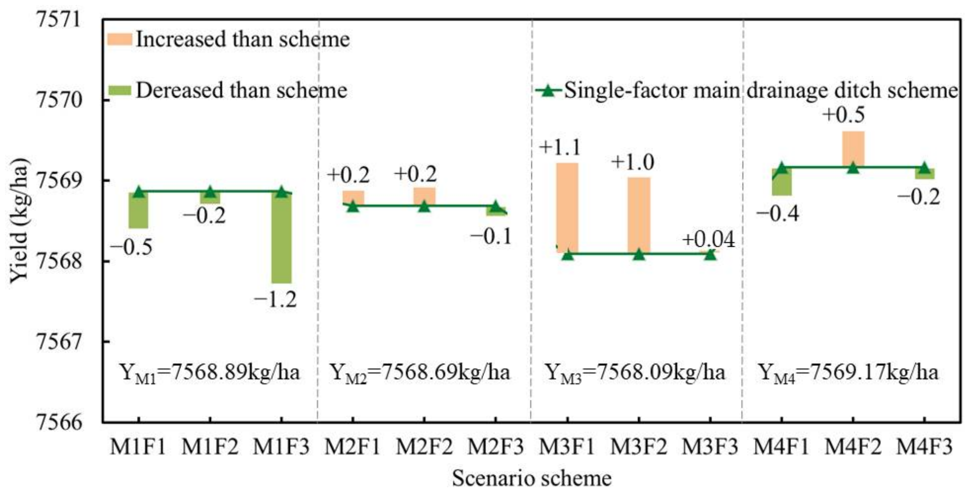
Figure 7c,d compared the crop yields under the combined control scheme and the single-factor field ditch scenario (F, the main ditch control scheme reflected the current situation). Compared with the single-factor field ditch schemes, the average yields of corn and wheat were increased by main ditch control by about 124.7 kg/ha and 5.5 kg/ha, respectively. The scenarios with the highest increases in corn and wheat yields were M2F2 and M4F2, respectively. By comparison with the crop yields of the single-factor main ditch scheme (i.e., the crop yield increases of the field ditch control scheme), the yields of corn and wheat increased by −0.1–29.8 kg/ha and −1.2–1.1 kg/ha, respectively. Ghane et al. [60] conducted a farm experiment in Ohio, USA, and found that under the condition of controlled drainage, smaller changes in the groundwater level would lead to smaller changes in the corn yield. The influence of main ditch control on groundwater level change was greater than that of field ditch control. Therefore, the effect of main ditch schemes on the crop yield was greater than that of field ditch schemes.

In conclusion, the combined main ditch and field ditch control schemes had a positive effect on crop growth in all of our combined control schemes, and the change in crop yield caused by the main ditch schemes was greater than that caused by the field ditch schemes. The yields of corn and wheat both increased under the combined control schemes, and the yield change of corn was greater than that of wheat.

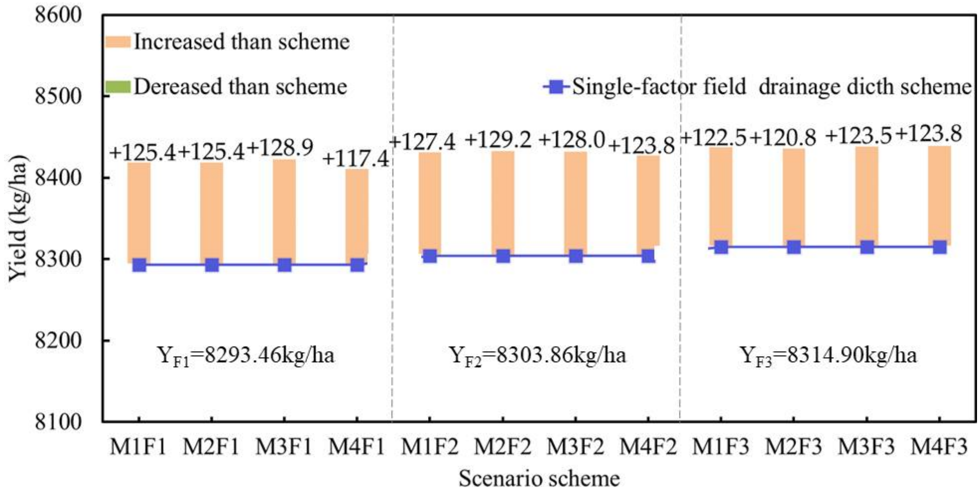


(**a**) Corn

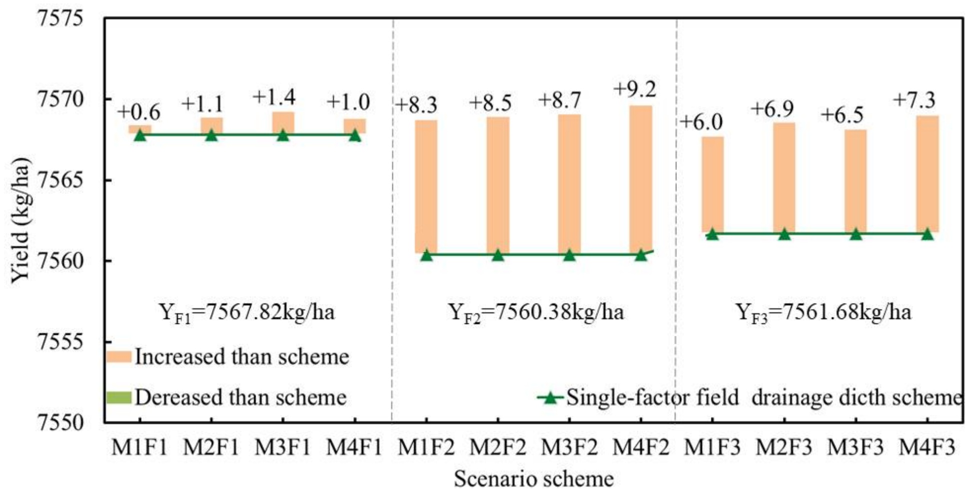
Figure 7. *Cont.*



(**b**) Wheat

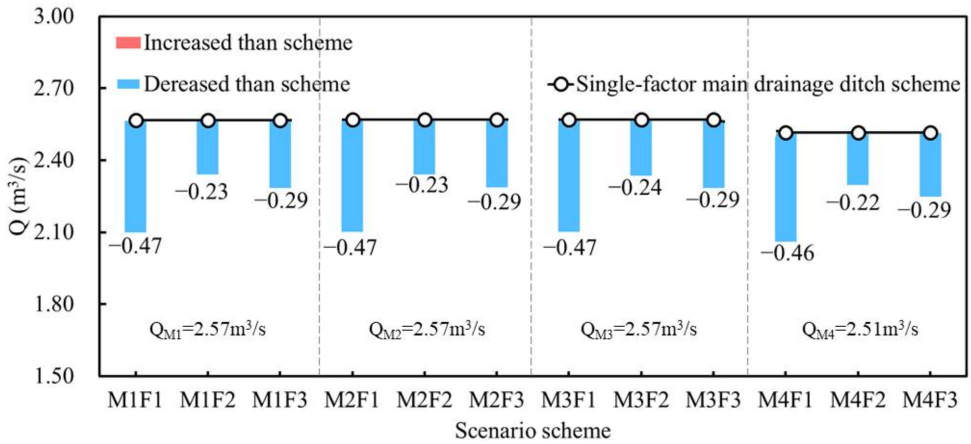


(**c**) Corn

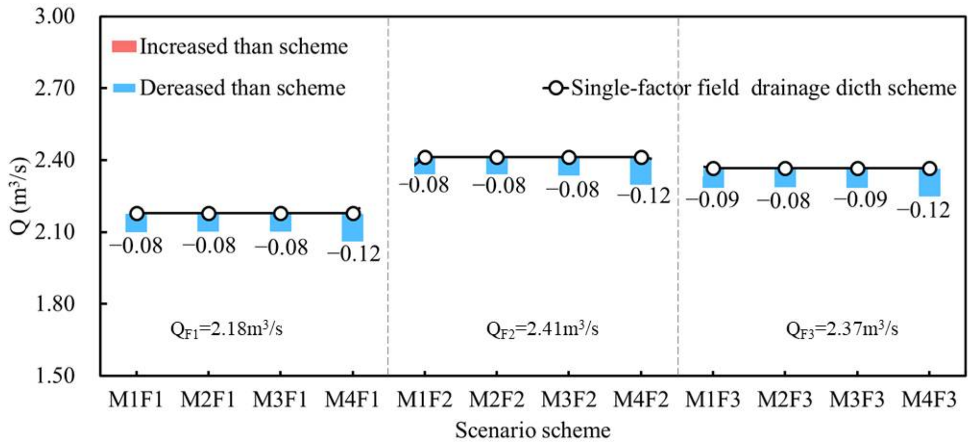


(**d**) Wheat

Figure 7. *Cont*.



(**e**) Comparison with the single-factor main ditch schemes



(**f**) Comparison with the single-factor filed ditch schemes

Figure 7. Comparison of crop yield and regional drainage discharge under the effect of combined control schemes. (**a**,**b**) Crop yield compared with the single-factor main ditch schemes; (**c**,**d**) the crop yield compared with the single-factor field schemes; (**e**,**f**) regional drainage discharge compared with the single-factor main ditch and filed ditch schemes. YM1–YM4: the crop yield under the single-factor main ditch schemes; YF1–YF3: the crop yield under the single-factor field ditch schemes; QM1–QM4: the Q under the single-factor main ditch schemes; QF1–QF3: the Q under the single-factor field ditch schemes.

3.3.2. Effects of Combined Control Schemes on Q

From Table 4, it can be seen that compared with the current situation scenario, the Q decreased. The scheme with the largest reduction in Q was M4F1, with a decrease of 0.64 m^3/s. Figure 7e,f compare the Q values under the combined control schemes and the single-factor main ditch schemes (M1–M4). Compared with the single-factor main ditch schemes, field ditch control led to a decrease in Q, and the schemes with the greatest reduction were combinations of main ditch schemes (M1–M4) and field ditch scheme F1, with an average reduction in Q of 0.47 m^3/s (Figure 7e). Compared with the single-factor field ditch schemes, main ditch control resulted in a small change in Q, and the schemes with the largest reduction in Q were combinations of main ditch scheme M4 and the field ditch schemes (F1–F3), with a reduction of approximately 0.12 m^3/s (Figure 7f). In general, the combined control schemes effectively reduced the Q and protected the water environment, and the field ditch schemes had a more significant emission-reduction effect than the main ditch schemes. Some studies have found that the reduction in pollutant concentrations is mainly associated with a reduction in Q [59–61]; Moloney et al. [62] found that level of connectivity of a surface ditch plays a major role in determining the magnitude of the P loss risk associated with a particular ditch. Therefore, the combined control schemes would effectively reduce the Q and farmland chemical emissions. The above results show that field ditch schemes were more effective in reducing emissions than main ditch schemes in all of our schemes.

In conclusion, combined main ditch and field ditch control schemes had a positive effect on reducing the Q and farmland non-point source pollution in this study. Under the combined control schemes, the Q was reduced, and field ditch schemes were more beneficial to reduce the Q than main ditch schemes. Compared with the current situation, the combined scheme that achieved both an increase in crop yield and decrease in Q was M4F3 (the top-five schemes that meet both the highest increasing values in crop yield and decreasing values in Q compared to the current situation are shown in Table 4).

4. Conclusions

In this paper, an open-ditch controlled drainage and crop yield simulation model (ODCDCYSM) was developed to simulate the drought and waterlogging situation and controlled drainage schemes in the 115.3 km^2 study area in the Northern Huaihe River Plain (NHRP) in Anhui Province, China. Based on the meteorological data from 1991 to 2021, different single-factor main ditch schemes, single-factor field ditch schemes, and the combined main ditch and field ditch control schemes were simulated to analyse the effects of each scheme on corn and wheat yields and regional drainage discharge (Q). By comparison with the current situation, a combined control scheme to reduce the Q while ensuring the normal growth of crops in the region was optimized. The main conclusions are as follows:

(1) The ODCDCYSM could accurately simulate the changes in groundwater level, main ditch water level and crop yields in the study area. The model provides an effective tool to quantify the effect on main and field ditches on regional drought and waterlogging situation reflected by crop yields and Q.

(2) Uppermost and downmost limits of main ditch water depth (UDLMDWD) in the dry season had little effect on corn and wheat yields and Q. The yield of crops increased with a decrease in UDLMDWD in the rainy season. The scenarios with larger Q values occurred when the UDLMDWD in the rainy season was low, and the Q increased by approximately 18.7% compared with the current situation.

(3) The crop yield and Q increased with an increase in the drainage spacing and drainage depth of the field ditch. With an increase in weir height, the crop yield and Q decreased. The corn and wheat yields were most affected by the weir height, followed by the drainage spacing and drainage depth of the field ditch. The wheat yield was less affected by changes in field ditch schemes.

(4) Combined control schemes could further improve the crop yield compared with either main ditch schemes or three-field ditch schemes. The effect of main ditch schemes was greater than that of field ditch schemes. Comparing corn and wheat, the corn yield increased by more than the wheat yield. Among the different schemes, the most significant yield increases occurred in the combination of main ditch schemes (M1–M4) and field ditch scheme F3 (with drainage spacing 400 m, drainage depth 1.6 m, ratio of weir height to drainage depth 1/2). The combined control schemes could further reduce the Q, and the effect on Q was greater for the field ditch schemes than for the main ditch schemes. The most significant reduction effects of Q occurred in the combination of main ditch schemes (M1–M4) and field ditch scheme F1 (drainage spacing 250 m, drainage depth 1.6 m, ratio of weir height to drainage depth 1/2).

(5) The combined scheme that achieved both increased crop yields and decreased Q was M4F3 (main ditch: sluices were the opened and closed at the ditch water depths of 3.5 m and 2.5 m in the dry season and at 3 m and 2 m in rainy the season; field ditch: drainage spacing 400 m, drainage depth 1.6 m, ratio of weir height to drainage depth 1/2).

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture12081167/s1, Figure S1. The rainfall and observed groundwater level change process of the representative field near the Chezhe ditch M2 (a) and far from the Chezhe ditch M5 (b) from 2015 to 2019. Table S1: Main parameters of surface runoff generation module; Table S2: Main parameters of ditch confluence module; Table S3. Main parameters of soil water and groundwater module; Table S4: Main parameters of crop growth module; Table S5: Comparison of observed and simulated crop yields (kg/ha); Table S6: The crop yield and regional drainage discharge (Q) under the single-factor main ditch water depth control schemes were better than the current situation; Table S7: The crop yield and regional drainage discharge (Q) under the single-factor field ditch control schemes were better than the current situation.

Author Contributions: Conceptualization, X.W. and J.H.; data curation, R.T.; formal analysis, R.T.; funding acquisition, X.W.; investigation, R.T., X.W., S.H., T.S., Y.W. and J.L.; methodology, X.W. and J.H.; project administration, X.W.; resources, X.W.; software, X.H. and R.T.; supervision, X.W.; validation, R.T. and X.H.; visualization, R.T. and Y.Y.; writing—original draft, R.T.; writing—review and editing, X.W. and X.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Science Foundation of China with grant number 51790532 and by the National Key Research and Development Program of China, grant number 2018YFC1508301.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: Thanks to the peer reviewers for improving our manuscript.

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

References

1. Etkin, D.; Medalye, J.; Higuchi, K. Climate warming and natural disaster management: An exploration of the issues. *Clim. Chang.* **2012**, *112*, 585–599. [CrossRef]
2. Schiermeier, Q. Droughts, heatwaves and floods: How to tell when climate change is to blame. *Nature* **2018**, *560*, 20–22. [CrossRef] [PubMed]
3. Lesk, C.; Rowhani, P.; Ramankutty, N. Influence of extreme weather disasters on global crop production. *Nature* **2016**, *529*, 84–87. [CrossRef] [PubMed]
4. Chen, H.; Liang, Z.; Liu, Y.; Jiang, Q.; Xie, S. Effects of drought and flood on crop production in China across 1949–2015: Spatial heterogeneity analysis with Bayesian hierarchical modeling. *Nat. Hazards* **2018**, *92*, 525–541. [CrossRef]
5. Zhang, Q.; Gu, X.; Singh, V.P.; Kong, D.; Chen, X. Spatiotemporal behavior of floods and droughts and their impacts on agriculture in China. *Glob. Planet. Chang.* **2015**, *131*, 63–72. [CrossRef]
6. Venkatappa, M.; Sasaki, N.; Han, P.; Abe, I. Impacts of droughts and floods on croplands and crop production in Southeast Asia—An application of Google Earth Engine. *Sci. Total Environ.* **2021**, *795*, 148829. [CrossRef] [PubMed]
7. Konar, M.; Dalin, C.; Suweis, S.; Hanasaki, N.; Rinaldo, A.; Rodriguez-Iturbe, I. Water for food: The global virtual water trade network. *Water Resour. Res.* **2011**, *47*, W05520. [CrossRef]
8. Fader, M.; Gerten, D.; Thammer, M.; Heinke, J.; Lotze-Campen, H.; Lucht, W.; Cramer, W. Internal and external green-blue agricultural water footprints of nations, and related water and land savings through trade. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 1641–1660. [CrossRef]
9. United Nations Transforming Our World: The 2030 Agenda for Sustainable Development. Available online: https://sdgs.un.org/2030agenda (accessed on 8 June 2022).
10. Shahzad, A.; Ullah, S.; Dar, A.A.; Fahad Sardar, M.; Mehmood, T.; Tufail, M.A.; Shakoor, A.; Haris, M. Nexus on Climate Change: Agriculture and Possible Solution to Cope Future Climate Change Stresses. *Environ. Sci. Pollut. Res.* **2021**, *28*, 14211–14232. [CrossRef] [PubMed]
11. Naftchali, A.D.; Jelodar, M.B.; Kholerdi, F.M.; Moftikolaei, M.A. Assessing socio-environmental sustainability at the level of irrigation and drainage network. *Sci. Total Environ.* **2020**, *731*, 138927. [CrossRef]
12. Paiao, G.D.; Fernández, F.G.; Naeve, S.L. Drainage Conditions Influence Corn-Nitrogen Management in the US Upper Midwest. *Agronomy* **2021**, *11*, 2491. [CrossRef]
13. Wang, Z.; Shao, G.; Lu, J.; Zhang, K.; Gao, Y.; Ding, J. Effects of controlled drainage on crop yield, drainage water quantity and quality: A meta-analysis. *Agric. Water Manag.* **2020**, *239*, 106253. [CrossRef]
14. Skaggs, R.W.; Fausey, N.R.; Evans, R.O. Drainage water management. *J. Soil Water Conserv.* **2012**, *67*, 167A–172A. [CrossRef]

15. Tan, C.S.; Drury, C.F.; Soultani, M.; van Wesenbeeck, I.J.; Ng, H.Y.F.; Gaynor, J.D.; Welacky, T.W. Controlled Drainage and Subirrigation Effects on Crop Yields and Water Quality. In Proceedings of the Drainage in the 21st Century: Food Production and the Environment, Orland, FL, USA, 8–10 March 1998; pp. 676–683.
16. Jouni, H.J.; Liaghat, A.; Hassanoghli, A.; Henk, R. Managing controlled drainage in irrigated farmers' fields: A case study in the Moghan plain, Iran. *Agric. Water Manag.* **2018**, *208*, 393–405. [CrossRef]
17. Shaoli, W.; Xiugui, W.; Brown, L.C.; Xingye, Q. Current status and prospects of agricultural drainage in China. *Irrig. Drain.* **2007**, *56*, S47–S58. [CrossRef]
18. Youssef, M.A.; Abdelbaki, A.M.; Negm, L.M.; Skaggs, R.; Thorp, K.R.; Jaynes, D.B. DRAINMOD-simulated performance of controlled drainage across the U.S. Midwest. *Agric. Water Manag.* **2018**, *197*, 54–66. [CrossRef]
19. Li, S.; Luo, W.; Jia, Z.; Tang, S.; Chen, C. The effect of natural rainfall on salt leaching under watertable management. *Land Degrad. Dev.* **2018**, *29*, 1953–1961. [CrossRef]
20. Jia, Z.; Luo, W.; Fang, S.; Wang, N.; Wang, L. Evaluating current drainage practices and feasibility of controlled drainage in the YinNan Irrigation District, China. *Agric. Water Manag.* **2006**, *84*, 20–26. [CrossRef]
21. Parsons, J.; Skaggs, R.; Doty, C. Simulation of controlled drainage in open-ditch drainage systems. *Agric. Water Manag.* **1990**, *18*, 301–316. [CrossRef]
22. Kröger, R.; Cooper, C.; Moore, M. A preliminary study of an alternative controlled drainage strategy in surface drainage ditches: Low-grade weirs. *Agric. Water Manag.* **2008**, *95*, 678–684. [CrossRef]
23. Wang, Y.; Wang, X.; Tang, G. Effects of Controlled Drainage of Main Ditch on Groundwater Table. *Tran. Chin. Soc. Agr. Eng.* **2008**, *6*, 74–77. [CrossRef]
24. Wang, Y.; Yu, F.; Shen, T. Study on the Technique and Effect of Controlled Drainage through the Main Drainage Ditch. *J. Hydraul. Eng.* **2013**, *6*, 104–110. [CrossRef]
25. Tang, R.; Han, X.; Wang, X.; Huang, S.; Yan, Y.; Huang, J.; Shen, T.; Wang, Y.; Liu, J. Optimized Main Ditch Water Control for Agriculture in Northern Huaihe River Plain, Anhui Province, China, Using MODFLOW Groundwater Table Simulations. *Water* **2022**, *14*, 29. [CrossRef]
26. Ren, X.; Wang, S.; Yang, P.; Tao, Y.; Chen, H. Performance Evaluation of Different Combined Drainage Forms on Flooding and Waterlogging Removal. *Water* **2021**, *13*, 2968. [CrossRef]
27. Guan, X.; Zang, Y.; Meng, Y.; Liu, Y.; Lv, H.; Yan, D. Study on spatiotemporal distribution characteristics of flood and drought disaster impacts on agriculture in China. *Int. J. Disaster Risk Reduct.* **2021**, *64*, 102504. [CrossRef]
28. Gao, C.; Zhang, Z.; Zhai, J.; Liu, Q.; Yao, M. Research on meteorological thresholds of drought and flood disaster: A case study in the Huai River Basin, China. *Stoch. Environ. Res. Risk Assess.* **2015**, *29*, 157–167. [CrossRef]
29. Chou, J.; Xian, T.; Dong, W.; Xu, Y. Regional Temporal and Spatial Trends in Drought and Flood Disasters in China and Assessment of Economic Losses in Recent Years. *Sustainability* **2019**, *11*, 55. [CrossRef]
30. Ojara, M.A.; Yunsheng, L.; Babaousmail, H.; Sempa, A.K.; Ayugi, B.; Ogwang, B.A. Evaluation of Drought, Wet Events, and Climate Variability Impacts on Maize Crop Yields in East Africa During 1981–2017. *Int. J. Plant Prod.* **2022**, *16*, 41–62. [CrossRef]
31. Ministry of Water Resources. *China Flood and Drought Disaster Bulletin*; China Water and Power Press: Beijing, China, 2018; pp. 50–54.
32. Zhang, Q.; Zhang, J.; Yan, D.; Wang, Y. Extreme precipitation events identified using detrended fluctuation analysis (DFA) in Anhui, China. *Theor. Appl. Climatol.* **2013**, *117*, 169–174. [CrossRef]
33. Zhu, H.; Wu, H.Z.; Zhang, L.P. Different Types of Disasters in Recent 10 Years in Anhui and Their Trend. *J. Catastrophol.* **2003**, *18*, 64–70.
34. Jing, W.; Luo, W.; Wen, J.; Jia. Zhonghua Analysis on the Effect of Controlled Drainage and Supplemental Irrigation on Crop Yield and Drainage. *J. Hydraul. Eng.* **2009**, *40*, 1140–1146.
35. Šimůnek, J.; Šejna, M.; Saito, H.; Sakai, M.; van Genuchten, M.T. *The HYDRUS-1D Software Package for Simulating the One-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media*; Version 4.17; Šimůnek, J., Ed.; Department of Environmental Sciences, University of California Riverside: Riverside, CA, USA, 2013.
36. Michel, C.; Andréassian, V.; Perrin, C. Soil Conservation Service Curve Number method: How to mend a wrong soil moisture accounting procedure? *Water Resour. Res.* **2005**, *41*, 1–6. [CrossRef]
37. Harbaugh, A.W.; Banta, E.R.; Hill, M.C.; Mcdonald, M.G. *MODFLOW-2005, the U.S. Geological Survey Modular Ground-Water Model—The Ground-Water Flow Proces*; U.S. Geological Survey: Reston, VA, USA, 2005.
38. Chanson, H. *Hydraulics of Open Channel Flow (Second Edition). Elsevier Butterworth-Heinemann*, 2nd ed.; Elsevier Butterworth-Heinemann: Waltham, MA, USA, 2004.
39. Dages, C.; Voltz, M.; Bsaibes, A.; Prévot, L.; Huttel, O.; Louchart, X.; Garnier, F.; Negro, S. Estimating the role of a ditch network in groundwater recharge in a Mediterranean catchment using a water balance approach. *J. Hydrol.* **2009**, *375*, 498–512. [CrossRef]
40. Skaggs, R.W.; Youssef, M.A.; Chescheir, G.M. DRAINMOD: Model use, calibration, and validation. *Trans ASABE* **2012**, *55*, 1509–1522. [CrossRef]
41. Skaggs, R.W.; Nassehzadeh-Tabriz, A. Design Drainage Rates for Estimating Drain Spacings in North Carolina. *Trans. ASAE* **1986**, *29*, 1631–1640. [CrossRef]
42. Williams, J.R. The erosion-productivity impact calculator (EPIC) model: A case history. *Trans ASAE* **1989**, *32*, 497–511. [CrossRef]
43. Wang, Z.; Ye, L.; Jiang, J.; Fan, Y.; Zhang, X. Review of application of EPIC crop growth model. *Ecol. Model.* **2022**, *467*. [CrossRef]

44. Balkovic, J.; van der Velde, M.; Schmid, E.; Skalský, R.; Khabarov, N.; Obersteiner, M.; Stürmer, B.; Xiong, W. Pan-European crop modelling with EPIC: Implementation, up-scaling and regional crop yield validation. *Agric. Syst.* **2013**, *120*, 61–75. [CrossRef]
45. Zhang, Y.; Wang, Y.; Liu, L. Function Mechanism Between the Drought and Waterlogging Disaster and the Soil-Structure of the Shajiang Soil in Huaibei Plain. *Prog. Geog.* **2001**, *2*, 169–176.
46. Anhui Provincial Bureau of Statistics. *An Hui Statistical Yearbook*; China Statistics Press: Beijing, China, 2018.
47. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Evapotranspiration. Guidelines for Computing Crop Water Requirements*; FAO: Roman, Italy, 1998.
48. Skaggs, R.W.; Youssef, M.A.; Chescheir, G.M.; Gilliam, J.W. Effect of drainage intensity on nitrogen losses from drained lands. *Trans. ASAE* **2005**, *48*, 2169–2177. [CrossRef]
49. Inam, A.; Adamowski, J.; Prasher, S.; Albano, R. Parameter estimation and uncertainty analysis of the Spatial Agro Hydro Salinity Model (SAHYSMOD) in the semi-arid climate of Rechna Doab, Pakistan. *Environ. Model. Softw.* **2017**, *94*, 186–211. [CrossRef]
50. Chen, Z.; Liu, X.; Zhu, B. Runoff estimation in hillslope cropland of purple soil based on SCS-CN model. *Trans. CSAE.* **2017**, *30*, 72–81. [CrossRef]
51. Moriasi, D.N.; Arnold, J.G.; Van Liew, M.W.; Bingner, R.L.; Harmel, R.D.; Veith, T.L. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. *Trans ASABE.* **2007**, *50*, 885–900. [CrossRef]
52. Xue, J.; Ren, L. Conjunctive use of saline and non-saline water in an irrigation district of the Yellow River Basin. *Irrig Drain.* **2017**, *66*, 147–162. [CrossRef]
53. Yang, J.; Zhu, Y.; Zha, Y.; Cai, S. *Mathematical Model and Numerical Method of Groundwater and Soil Water Movement*; Science Press: Beijing, China, 2016.
54. Zhao, J.; Wang, W.; Wang, Z.; Wang, X.; Xie, H.; Wang, X. Spatial Variability of Streambed Hydraulic Conductivity in the Lower Reaches of the Luanhe River. *Hydroge Eng. Geol.* **2014**, *41*, 13–20. [CrossRef]
55. Zhou, J. *Rational Allocation of Multi-Source Water Resources for Economic Development Zone of Taihe County*; Hefei University of Technology: Hefei, China, 2021.
56. FAO. Crop Water Information. Available online: http://www.fao.org/land-water/databases-and-software/crop-information/en/ (accessed on 8 June 2022).
57. Acharya, U.; Chatterjee, A.; Daigh, A.L.M. Effect of Subsurface Drainage Spacing and Depth on Crop Yield. *Agron. J.* **2019**, *111*, 1675–1681. [CrossRef]
58. Ghane, E.; Askar, M.H. Predicting the effect of drain depth on profitability and hydrology of subsurface drainage systems across the eastern USA. *Agric. Water Manag.* **2021**, *258*, 107072. [CrossRef]
59. Muhammad, E.; Ibrahim, M.; El-Sayed, A. Effects of drain depth on crop yields and salinity in subsurface drainage in Nile Delta of Egypt. *Ain Shams Eng. J.* **2021**, *12*, 1595–1606. [CrossRef]
60. Ghane, E.; Fausey, N.R.; Shedekar, V.; Piepho, H.-P.; Shang, Y.; Brown, L.C. Crop yield evaluation under controlled drainage in Ohio, United States. *J. Soil Water Conserv.* **2012**, *67*, 465–473. [CrossRef]
61. Chen, K.; Yu, S.; Ma, T.; Ding, J.; He, P.; Li, Y.; Dai, Y.; Zeng, G. Modeling the Water and Nitrogen Management Practices in Paddy Fields with HYDRUS-1D. *Agriculture* **2022**, *12*, 924. [CrossRef]
62. Moloney, T.; Fenton, O.; Daly, K. Ranking connectivity risk for phosphorus loss along agricultural drainage ditches. *Sci. Total Environ.* **2020**, *703*, 134556. [CrossRef] [PubMed]