water

MDPI

Article

# Quantitative Assessment Model for the Effects of Drought Mitigation on Regional Agriculture Based on an Expectation Index of Drought Mitigation Effects

**Yuliang Zhang [1], Juliang Jin [2], Shangming Jiang [3,*], Shaowei Ning [2], Yuliang Zhou [2] and Zhiyong Wu [1]**

1 College of Hydrology and Water Resources, Hohai University, Nanjing 210098, China; zhangyuliang@hhu.edu.cn (Y.Z.); wzyhhu@gmail.com (Z.W.)
2 School of Civil Engineering, Hefei University of Technology, Hefei 230009, China; JINJL66@126.com (J.J.); ning@hfut.edu.cn (S.N.); zyl54600@163.com (Y.Z.)
3 Key Laboratory of Water Conservancy and Water Resources of Anhui Province, Water Resources Research Institute of Anhui Province and Huaihe River Commission, MWR, Hefei 230088, China
* Correspondence: jiangshangming@163.com; Tel.: +86-180-5607-9675

Received: 8 January 2019; Accepted: 27 February 2019; Published: 5 March 2019

**Abstract:** The extent of water deficit and drought loss mitigation, through human activities such as defense, mitigation, and resistance to drought risk, is revealed by its effects on agriculture. To analyze the distribution regularities of the effects of drought mitigation on agriculture and to provide better insight on drought mitigation actions, an expectation index of drought mitigation effects (EDRE) was formulated based on the definitions of the drought system. The crop yield when no drought mitigation measures were implemented was calculated via tests and simulations, and expectations of drought-related yield loss with and without drought mitigation measures (EDRL and EDRM, respectively) were calculated in the drought loss risk assessment model. Then, a quantitative assessment model for the effects of drought mitigation on regional agriculture was built. Using a case study from the Huaibei Plain in the Anhui Province of China, it was found that drought mitigation effects decrease gradually from North to South. Moreover, small values of drought mitigation effects correspond to large EDRM and small EDRL values. It is necessary to urgently improve drought mitigation measures in locations where EDRE is small and EDRL is large, or where EDRE is small and EDRM is large. The main drought mitigation measures were identified through correlation analysis. Additionally, the adaptation of drought mitigation measures to local conditions leads to a spatial distribution regularity.

**Keywords:** drought mitigation effects assessment; crop yield loss rate; drought mitigation effects expectation index; crop water production function; drought loss risk assessment; information diffusion; Huaibei Plain in Anhui Province

## 1. Introduction

With global climate change and the intensification of human activities, the impact of droughts worldwide is increasing [1,2]. Countries are increasingly concerned about food security and water safety issues, making drought risk assessment and risk management research an important topic of research in disaster science and water management [3], and a strategic shift from initial crisis management to risk management has been achieved [4]. Drought mitigation is an important part of the quantitative assessment of drought risk [5], while the effects of drought mitigation are a concentrated expression of drought mitigation. Research on various drought mitigation aspects provides an important empirical basis for countries to further strengthen the construction of water conservancy facilities [6]. Hence, many scholars have researched drought mitigation measures, such as the adoption of certain methods of cultivation [7–9], soil treatments [10,11], or crop treatments [12–17]. Some indicators were used to quantify the effects of drought mitigation, such as leaves parameters [7,9–13,15–17], dry matter quality [7,12,14,17], plant height [10,12,17], water content [9,13], and crop yield [7,8,11]. Sun et al. [10] comprehensively evaluated the effects of drought mitigation measures to determine the best drought mitigation method. Chen et al. [6] investigated drought mitigation measures in a total of seven provinces and cities in China, characterized grain yield reduction as the drought mitigation effect, established the econometric model of drought mitigation effects of farmland water conservancy facilities, and calculated the regression relationship between grain yield reduction and drought mitigation factors. On this basis, the effects of different drought mitigation measures were analyzed according to the regression coefficients of drought mitigation measures.

While the role of drought mitigation measures has been widely researched by government departments and scholars, and the effects of different drought mitigation measures have been analyzed using experimental or survey data [6], little attention has been paid to quantifying the drought mitigation effects in different regions and analyzing regional differences. To evaluate regional variations in drought mitigation effects and reasonably distribute investments for inter-regional agricultural drought mitigation, this study defined the expectation index of drought mitigation effects based on existing research and the shortcomings of comprehensive drought mitigation, to quantitatively evaluate the effects of agricultural drought mitigation. Next, an assessment model for regional drought mitigation effects, based on the experiment and simulation, was developed and applied to a case study site in China to provide a theoretical basis for regional drought mitigation measures.

## 2. Materials and Methods

Based on the principle of water balance, the actual evapotranspiration of crops under no drought mitigation measures was calculated. Crop yield was calculated according to the crop water production function, determined by the experimental data. Furthermore, a quantitative analysis of the risk of drought loss was carried out using the yield with and without drought mitigation measures. On this basis, the distribution of the effects of agricultural drought mitigation in each region was calculated.

### *2.1. Study Area and Data*

The chosen study area was the Huaibei Plain in the Anhui Province (hereafter referred to as the study site), located North of the Huaihe River in China. This site belongs to the mid-latitude zone of Eastern China (see Figure 1). Agricultural development in this area is very important to the local economy and food security, as it belongs to a rich light resource field, with 2200–2450 sunshine hours annually. This situation contributes to optimal growth conditions for local crops: The Huaibei Plain provides a key commodity grain base in China, particularly that of winter wheat, which is the most commonly grown crop. However, droughts are relatively prominent natural disasters in this region and can severely impact local agricultural production and development [18,19]. Furthermore, considering that winter wheat is usually sown in October and harvested in May of the following year, the growing period for this crop is during the non-rainy season, making its cultivation more prone to drought risk. Therefore, winter wheat in the study site was used as an example for this study. In 1976–1978, 1985–1986, 1988–1989, 1991–1992, 1994, 1997, and 1999–2001, the drought area exceeded 25% of the total agricultural acreage. Such high frequency of droughts highlights the urgency to assess local drought mitigation effects, provide guidance for regional drought mitigation engineering planning, and reduce the adverse effects of drought on the local agriculture.

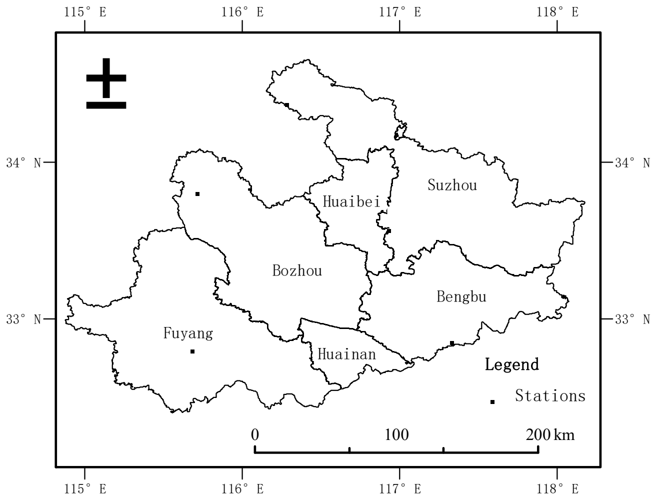


**Figure 1.** Administrative division map of the Huaibei Plain in the Anhui Province of China.

Data: (a) The meteorological data collected were daily rainfall, maximum and minimum temperature, relative humidity, average wind speed, and sunshine hours at five stations in Suzhou, Bozhou, Dangshan, Bengbu, and Fuyang from 1975 to 2007. The location of each station is shown in Figure 1. Data were obtained from the China Meteorological Data Service Center and reports from the Anhui and Huaihe River Institute of Hydraulic Research. To deal with uncertainty caused by using different data, time series of meteorological data were tested using the homogeneity test based on observation data and the t-test. The data passed the homogeneity test and its quality was considered reliable; and (b) the groundwater depth data recorded from 1975 to 2007 were obtained from reports of the Anhui and Huaihe River Institute of Hydraulic Research.

### *2.2. Simulation-Based Potential Evapotranspiration of Crops and Groundwater Use without Drought Mitigation Measures*

Crop potential evapotranspiration is defined as the transpiration of crops under sufficient irrigation conditions and can be obtained through multiplying reference crop evapotranspiration $ET_0$ [20] by crop coefficients $K_c$. Additionally, groundwater utilization refers to the amount of water [21] that is transported from the phreatic groundwater to the unsaturated zone under the crop growth condition, namely the phreatic evaporation [22], some of which is used for crop transpiration and some of which evaporates between crops. Based on the most widely used Aviriyanov formula [23], the following formula (1) was used to calculate the groundwater utilization of the crop. Next, according to the relevant test data, the formula parameters for crop groundwater use were calibrated using the Accelerated Genetic Algorithm (AGA) and the groundwater use formula was obtained:

$$E_{g,i} = ET_{c,i}\left(1 - \frac{H_i}{H_{\max}}\right)^n \tag{1}$$

where $E_{g,i}$ is the amount of groundwater used in the $i$-th time unit (mm/d); $ET_{c,i}$ is the actual evapotranspiration of crops in the $i$-th time unit (mm/d); $H_i$ is the groundwater depth of the crops in the $i$-th time unit (m); $H_{\max}$ is the groundwater depth where the utilization amount of crop groundwater is 0, and 3 m is selected as $H_{\max}$ in the study site; and $n$ is the empirical constant, calibrated by AGA using experimental data.

### *2.3. Simulation-Based Actual Evapotranspiration of Crops without Drought Mitigation Measures*

Based on potential evapotranspiration and groundwater use, the actual evapotranspiration of crops without drought mitigation measures was calculated. Actual crop evapotranspiration refers to the crop evapotranspiration influenced by actual soil water content and can be calculated using the crop water demand $ET_{ct}$, based on the water balance principle. When the soil water content of crops is low, the actual crop water demand $ET_{ct}$ decreases. The actual water requirement $ET_{ct,i}$ for the $i$-th period was calculated as follows [24]:

$$ET_{ct,i} = \begin{cases} ET_{cp,i} & 0.75 \leq r_i \leq 1.00 \\ 0.80ET_{cp,i} & 0.50 \leq r_i < 0.75 \\ 0.35ET_{cp,i} & s_d \leq r_i < 0.50 \\ 0.00 & 0.00 \leq r_i < s_d \end{cases} \tag{2}$$

where $ET_{ct,i}$ is the potential evapotranspiration of the crop calculated by the Penman formula in the $i$-th period under the full irrigation condition (mm/d); $s_d$ is the wilting moisture content; and $r_i$ is the ratio of soil water content to field water-holding capacity in the $i$-th period:

$$r_i = \frac{s_i}{s_s} \tag{3}$$

where $s_i$ is the soil moisture content at the initial time in the $i$-th period (mm); and $s_s$ is the field capacity (mm).

When the actual water requirement $ET_{ct,i}$ of the crop is large, the crop absorbs water from groundwater, daily rainfall, and soil water. When the soil water content becomes lower than the wilting moisture content $s_d$, the crop would no longer absorb water from the soil [25]. Therefore, the crop actual evapotranspiration $ET_{c,i}$ was calculated as below [26]:

$$ET_{c,i} = \begin{cases} ET_{ct,i} & ET_{ct,i} < P_i + (s_i - s_d) + E_{g,i} \\ E_{g,i} + P_i + (s_i - s_d) & ET_{ct,i} \geq P_i + (s_i - s_d) + E_{g,i} \end{cases} \tag{4}$$

where $ET_{c,i}$ is the crop actual evapotranspiration for the $i$-th period (mm/d); $P_i$ is the rainfall of the $i$-th period (mm/d); and $s_d$ is the wilting moisture content (mm).

Based on the principle of water balance, the soil water content of a particular crop at the end of the period is the initial soil water content minus the amount of water consumed by crop growth plus the amount of rainfall, but the soil moisture content has a threshold, with upper and lower limits. Hence, if it exceeds the limits, it would remain at the critical level, and the detailed calculation method is shown below [25]:

$$s_{i+1} = \begin{cases} s_i + P_i & ET_{c,i} \leq E_{g,i}, s_i + P_i < s_s \\ s_s & \begin{array}{l} ET_{c,i} \leq E_{g,i}, s_i + P_i \geq s_s \\ or\ ET_{c,i} > E_{g,i}, s_i + P_i - (ET_{c,i} - E_{g,i}) \geq s_s \end{array} \\ s_i + P_i - (ET_{c,i} - E_{g,i}) & ET_{c,i} > E_{g,i}, s_d < s_i + P_i - (ET_{c,i} - E_{g,i}) < s_s \\ s_d & ET_{c,i} > E_{g,i}, s_i + P_i - (ET_{c,i} - E_{g,i}) \leq s_d \end{cases} \tag{5}$$

where $s_{i+1}$ is the initial soil water content at the $i$ + 1 period (mm).

*2.4. Construction of Crop Water Production Function Based on the Experiment*

The crop water production function refers to the functional relationship between crop actual evapotranspiration and crop yield. The Jensen model, with an extensive application, was used to establish the crop water production function [27]:

$$\frac{y}{y_m} = \prod_{j=1}^{J} \left( \frac{ET_{c,j}}{ET_{m,j}} \right)^{\lambda_j} \tag{6}$$

where $y$ is the actual yield of crops (kg/hm$^2$); $y_m$ is the crops potential production (kg/hm$^2$); $j$ is the $j$-th growth period of crops ($j$ = 1, 2, . . . , $J$); $ET_{c,j}$ is the daily average actual evapotranspiration of crops at the $j$-th growth period (mm/d); $ET_{m,j}$ is the daily potential evapotranspiration of crops at the $j$-th growth period (mm/d); $\lambda_j$ is the water deficiency sensitive index of crops at the $j$-th growth period, showing the influence of the water deficiency of the $j$-th growth period on the production; and $\lambda_j$ is calibrated using the experimental data.

By designing the experiment, $y$, $y_m$, $ET_{c,j,k}$, and $ET_{m,j,k}$ can be calculated in multiple experimental schemes, and the water deficiency sensitive index $\lambda_j$ during all crop growth periods can be calibrated using AGA. The sum of the calculation error in the different experimental schemes was considered to be the objective function:

$$S = \sum_{k=1}^{K}\left(\prod_{j=1}^{J}\left(\frac{ET_{c,j,k}}{ET_{m,j,k}}\right)^{\lambda_j} - \frac{y_k}{y_m}\right)^2 \tag{7}$$

where $S$ is the objective function; $ET_{c,j,k}$, $ET_{m,j,k}$ is the daily average actual evapotranspiration and daily average potential evapotranspiration at the $j$-th growth period in the $k$-th scheme, respectively, (mm/d); $y_k$ is the actual production of crops in the $k$-th scheme (kg/hm$^2$); and $K$ is the total amount of experiment schemes. The lower the objective function, the better the calibration effect.

Using the water deficiency sensitive index $\lambda_1, \lambda_2, \ldots, \lambda_j$ in each growth period as the optimization variables, the constraint condition was set according to the general value range of the water deficiency sensitive index [27], the formula (7) was considered to be the objective function, and the water deficiency sensitive index in each growth period could be obtained using AGA.

To quantitatively analyze the effects of agricultural drought mitigation, crop yield reduction and drought loss risk with and without drought mitigation measures (EDRM and EDRL, respectively) need to be calculated, and the effects of agricultural drought mitigation can be obtained through the comparison of results in both conditions.

### 2.5. Quantitative Assessment Model of Drought Loss Risk

Crop production was calculated according to the water production function without drought mitigation measures. Next, the crop yield reduction rate $x_i$ of the $i$-th year for drought was computed:

$$x_i = \begin{cases} 0 & \frac{y_m - y_i}{y_m} < 0 \\ \frac{y_m - y_i}{y_m} & \frac{y_m - y_i}{y_m} \geq 0 \end{cases} \tag{8}$$

The information diffusion based on AGA and the cross-validation was used to calculate the EDRL in the study area [28], and the quantitative assessment model of drought loss risk was built [29]. There are two steps in this assessment model, the first step is to calculate a diffusion coefficient:

$$\left.\begin{array}{c} \min CV(h) \\ h_{\min} \leq h \leq h_{\max} \end{array}\right\} \tag{9}$$

$$CV(h) = \int_{a_0}^{b_0} \hat{f}^2(x)dx - \frac{2}{n}\sum_{i=1}^{n}\hat{f}^{(i)}(x_i) \tag{10}$$

$$\hat{f}(x) = \frac{1}{\sqrt{2\pi}nh}\sum_{j=1}^{n}\exp\left[-\frac{(x-x_j)^2}{2h^2}\right] \tag{11}$$

$$\hat{f}^{(i)}(x_i) = \frac{1}{\sqrt{2\pi}nh}\sum_{\substack{j=1 \\ j\neq i}}^{n}\exp\left[-\frac{(x_i-x_j)^2}{2h^2}\right] \tag{12}$$

where $h$ is the optimization variable; [$h_{\min}$, $h_{\max}$] is the variation range of $h$; $n$ is the number of samples; $\hat{f}(x)$ is the estimated probability density at the point of $x$; $a_0$ is the minimum of samples data range; $b_0$ is the maximum of samples data range; and $\hat{f}^{(i)}(x_i)$ is the estimated probability density at the point of $x_i$ without using the point $x_i$ information.

Further, the second step is to calculate the EDRL:

(a) Determine the universe of the crop yield reduction rate:

$$\boldsymbol{U} = \{u_1, u_2, \cdots u_j, \cdots u_m\} \tag{13}$$

where $u_j$ is the number in the universe.

(b) Calculate the estimated probability density at the $u_j$:

$$f_i(u_j) = \frac{1}{\sqrt{2\pi}h} \exp\left[-\frac{(u_j - x_i)^2}{2h^2}\right] \tag{14}$$

(c) Let:

$$C_i = \sum_{j=1}^{m} f_i(u_j) \tag{15}$$

Then, the membership function of the fuzzy subset is:

$$\mu_i(u_j) = \frac{f_i(u_j)}{C_i} \tag{16}$$

(d) Let:

$$q(u_j) = \sum_{i=1}^{n} \mu_i(u_j) \tag{17}$$

$$Q = \sum_{j=1}^{m} q(u_j) \tag{18}$$

The frequency of all samples with the crop yield reduction rate of $u_j$ is:

$$p(u_j) = \frac{q(u_j)}{Q} \tag{19}$$

EDRL was then calculated according to the following formula [30]:

$$EDRL = \int_0^1 xf(x)dx \approx \sum_{j=1}^{m} u_j p(u_j) \tag{20}$$

where $x$ is the rate of yield reduction due to drought; $f(x)$ is the probability density at $x$; and $u_j$ is the $j$-th point in the domain ($j$ = 1, 2, ... , $m$); and $p(u_j)$ is the frequency value of the sample point falling at $u_j$.

In the calculation of crop drought loss risk, drought mitigation engineering measures such as actual water conservancy conditions and other non-engineering measures would influence drought loss. Therefore, the method of linear sliding average [28], combined with crop actual yields from the yearbook, was used to calculate the actual crop yield reduction rate. However, the factors influencing the actual yield reduction rate include not only drought, but also flood disaster. It is necessary to determine if the particular year was a drought year. If the year did not include a drought, the drought reduction rate is 0. Therefore, the calculation method of the crop drought reduction rate $x_a(i)$ under actual prevention measures on the $i$-th year is [31]:

$$x_a(i) = \begin{cases} 0 & \frac{s_f}{s_d+s_f} \geq 20\% \\ \max(-x_q(i),\ 0) & \frac{s_f}{s_d+s_f} < 20\% \end{cases} \quad (21)$$

where $s_f$ is the inundated area from flood disaster in the $i$-th year (hm$^2$); $s_d$ is the area affected by drought in the $i$-th year (hm$^2$); and $x_q(i)$ is the relative meteorological yield in the $i$-th year.

Combined with the drought-related yield loss rate $x_a(1), x_a(2), \ldots, x_a(n)$, the frequency of different crop yield reduction rate and the EDRM can be calculated based on the information diffusion of cross-validation [28] in the study area.

### 2.6. Quantitative Assessment Model of Field Agricultural Drought Mitigation Effects

Droughts are typically complex systems [32], including the interaction of disaster-inducing factors, disaster-bearing bodies, disaster prevention and mitigation measures (drought mitigation), and disaster-stricken environments, which cause drought loss. Drought-resistant effects are the concentrated reflection of drought-resistant abilities, which refer to the role of various human activities to prevent, mitigate, and resist the effects of drought in a specific area [6,33]. In 1995, Li et al. [34] tried to calculate the difference of actual yield and natural yield as the increased yield for drought mitigation. While this was not regarded as an evaluation index for the drought mitigation effect, we can still draw from this paper [34]. From their definition of drought mitigation effects, under a certain drought loss risk, the amount of the drought loss recovered by drought mitigation measures can be regarded as a measure of drought mitigation effects [6–8,11]. Combined with the definition of the drought system [32], when calculating the drought loss prevented by mitigation measures, the drought losses caused by the interaction of disaster-inducing factors, disaster-bearing bodies, and the environment of disaster-prevention can be first calculated; that is, drought loss without drought measures can be determined. Next, we added the impact of drought mitigation measures to calculate drought losses caused by the interaction of disaster-inducing factors, disaster-stricken bodies, disaster prevention and mitigation measures, and disaster-stricken environment; that is, drought losses under actual drought mitigation measures were determined. The difference between the two drought losses is just the drought loss prevented by drought mitigation measures. Therefore, the drought mitigation effect can be defined as:

$$x_{R,i} = x_{N,i} - x_{A,i} \quad (22)$$

where $x_{R,i}$ is the drought mitigation effect index under a certain drought loss risk on the $i$-th field, the amount of drought loss that mitigation measures can recover under a certain drought loss risk; $x_{N,i}$ is the drought loss without drought mitigation measures under a certain drought loss risk on the $i$-th field; and $x_{A,i}$ is the drought loss through the intervention of mitigation measures under a certain risk of drought loss on the $i$-th field.

Considering that the expected loss can be considered as a measure of risk [30], in order to quantify drought losses recovered by mitigation measures under different drought loss risks, and to facilitate the comparison of drought mitigation effects among regions, the expected value of drought mitigation effects index (EDRE) can be viewed as a measure of regional drought mitigation effects:

$$Ex_{R,i} = E(x_{N,i} - x_{A,i}) = Ex_{N,i} - Ex_{A,i} \quad (23)$$

where $Ex_{R,i}$ is the EDRE on the $i$-th field, and the expected amount of drought loss that mitigation measures can recover; $Ex_{N,i}$ is the expectation of drought loss without mitigation measures on the $i$-th field; and $Ex_{A,i}$ is the expectation of drought loss under the actual mitigation measures on the $i$-th field. Crop drought loss is always measured according to the drought-related yield loss. Therefore, $Ex_{N,i}$ is the EDRL on the $i$-th field, which can be calculated using formula (20), and $Ex_{A,i}$ is the EDRM on the $i$-th field. The EDRE was used to assess the distribution pattern of the agricultural drought mitigation effects in each field, and the quantitative assessment model of the regional agricultural drought mitigation effects was built. The EDRE is an effect index for all the drought mitigation measures, not an index for a unit measure.

## 3. Results

### 3.1. Actual Evapotranspiration Calculation of Wheat Based on the Simulation

According to Formulas (2)–(5), the principle of water balance was used to compute the actual evapotranspiration of wheat. The detailed calculation steps are:

(a) The potential evapotranspiration $ET_{cp}$ and groundwater utilization $E_g$ of wheat were calculated every ten days.
(b) The actual water demand $ET_{ct,1}$ of wheat in the first ten days was calculated. According to the potential evapotranspiration $ET_{cp,1}$ and the ratio $r_1$ of the initial soil water content and the field capacity, $ET_{ct,1}$ was computed and combined with formula (2) in each region. Due to the limited data, initial $r_1$ is 75%.
(c) The actual evapotranspiration $ET_{c,1}$ of wheat was calculated in the first ten days. $P_1$, $E_{g,1}$, $ET_{ct,1}$, and $s_1$ were substituted into formula (4) to calculate $ET_{c,1}$, where $s_1$ was calculated according to the initial $r_1$ of 75%; soil moisture content of the field capacity is found to be 28% in the Huaibei Plain. Soil water content at a depth of 40 cm was generally considered to be the amount of water that can be absorbed by the crop. The surface soil bulk density in the Huaibei Plain is 1.4 g/cm$^3$. The soil water content per unit area is:

$$s_1 = 40 \times 1.4 \times 0.28 \times 0.75 \times 10 = 117.6 \text{ mm}$$

According to Reference [35], the wilting moisture content of the soil in sandy soil is 0.0063 kg/kg. Therefore, the wilting moisture content $s_d$ per unit area is:

$$s_d = 40 \times 1.4 \times 0.0063 \times 10 = 3.5 \text{ mm}$$

(d) The initial soil water content $s_2$ of the next ten-day period was calculated. $s_1$, $P_1$, $ET_{c,1}$, and $E_{g,1}$ were substituted in Formula (5) to calculate $s_2$:

$$s_2 = 40 \times 1.4 \times 0.28 \times 10 = 156.8 \text{ mm}$$

(e) Steps (b)–(d) were repeated to calculate the actual evapotranspiration $ET_c$ of wheat every ten days.

### 3.2. Building the Crop-Water Production Function Based on the Experiments

#### 3.2.1. Experimental Design

In order to analyze the relationship between evapotranspiration and yield in different growth periods for wheat, crop experiments were carried out in pits at the Xinmaqiao Experiment Station in Huaibei plain in 2011. Control factors were soil moisture and growth stages, where the soil water content control was set as three sections: Light, middle, and heavy drought. The growth stages were divided into the tillering stage, jointing stage, heading stage, and milk-ripe stage. Different treatment samples were treated with different soil moisture lower limits at different growth stages and were finally grouped, as shown in Table 1.

**Table 1.** Different treatment schemes for wheat drought experiments at Xinmaqiao test station.

| Treatment Number | Test Pit Number | The Lower Limit of Soil Moisture at Each Growth Stage | | | | Remarks |
|---|---|---|---|---|---|---|
| | | Tillering Stage | Jointing Stage | Heading Stage | Milk-Ripe Stage | |
| A | X3, X5, Z3, S3 | 65% | 70% | 70% | 65% | No drought treatment. |
| B | X1, Z1 | 50% | 70% | 70% | 65% | Light drought in the tillering stage |
| C | X2, X18, S2 | 40% | 70% | 70% | 65% | Middle drought in the tillering stage |
| D | X11, Z2 | 30% | 70% | 70% | 65% | Severe drought in the tillering stage |
| E | X10, Z4 | 65% | 55% | 70% | 65% | Light drought in the jointing stage |
| F | X4, X9, S5 | 65% | 45% | 70% | 65% | Middle drought in the jointing stage |
| G | X12, S7 | 65% | 35% | 70% | 65% | Severe drought in the jointing stage |
| H | X7, S6 | 65% | 70% | 55% | 65% | Light drought in the heading stage |
| I | X6, X17, Z5 | 65% | 70% | 45% | 65% | Middle drought in the heading stage |
| J | X14, S8 | 65% | 70% | 35% | 65% | Severe drought in the heading stage |
| K | X13, S4 | 65% | 70% | 70% | 50% | Light drought in the milk-ripe stage |
| L | X8, X15, Z6 | 65% | 70% | 70% | 40% | Middle drought in the milk-ripe stage |
| M | X16, S1 | 65% | 70% | 70% | 30% | Severe drought in the milk-ripe stage |

#### 3.2.2. Experimental Process

The samples were treated by the same fertilization, weeding, and spraying pesticide, considering the same lower limit of soil moisture at the seedling stage. Starting from the tillering stage, different treatment groups were processed with different lower limits of soil moisture (shown in Table 1). Soil moisture content was measured every ten days or so, and irrigation was carried out according to the control conditions set by the test. Additionally, daily measurements included meteorological data such as sunshine hours, precipitation, relative humidity, average wind speed, and maximum and minimum air temperature. After the wheat harvest on 31 May, wheat grain amount was calculated to determine the yield of each pit.

#### 3.2.3. Test Data Processing

Throughout the experiment, the soil moisture content, rainfall, irrigation water volume, and drainage water volume were obtained from the measuring pits for every growth stage. According to the "Irrigation experiment standard" [36], the actual evapotranspiration $ET_{a,i}$ of the $i$-th growth period was calculated:

$$ET_{a,i} = 10\sum_{j=1}^{J} \gamma_j H_j (W_{j1} - W_{j2}) + M + P + K - C \tag{24}$$

where $j$ is the soil layer number, and $J$ is the total amounts of soil layers, and $\gamma_j$ is the volume-weight of the $j$-th soil layer (g/cm$^3$); $H_j$ is the thickness of the $j$-th soil layer (cm); $W_{j1}$ is the soil moisture content of the $j$-th soil layer at the beginning of one period; $W_{j2}$ is the soil moisture content of the $j$-th soil layer at the end of the period; $M$ is the irrigation water volume within the period (mm); $P$ is the precipitation within the period (mm); $K$ is the groundwater use (mm); and $C$ is the drainage water volume (mm). Actual evapotranspiration in the first treatment is also the maximum evapotranspiration under an adequate water supply. Therefore, it is considered to be the potential evapotranspiration $ET_{m,i}$ for the $i$-th growth period of the crop.

#### 3.2.4. Parameters Calibration of Water Production Function Based on the AGA

According to the data obtained in China, the general range [27] of the water scarcity sensitivity index of wheat is:

$$0.02 < \lambda_j < 0.48 (j = 1, 2, 3, 4) \tag{25}$$

Combined with the collected data, the AGA was used to calibrate $\lambda_j$ in the water production function with an objective function of Formula (7). The results are shown in Table 2.

**Table 2.** The water scarcity sensitivity index $\lambda_j$ calibrated by the different methods for different growth periods in the study site.

| Methods | The Water Scarcity Sensitivity Index $\lambda_j$ | | | | Correlation Coefficient $R$ |
|---|---|---|---|---|---|
| | Tillering Stage | Jointing Stage | Heading Stage | Milk-Ripe Stage | |
| Accelerating Genetic Algorithm | 0.163 | 0.023 | 0.341 | 0.108 | 0.920 |
| Reference [37] | 0.169 | 0.018 | 0.340 | 0.110 | 0.846 |

According to the optimized results shown in Table 2, the water production function of wheat yield was obtained:

$$\frac{Y}{Y_m} = \left(\frac{ET_{a,1}}{ET_{m,1}}\right)^{0.163} \left(\frac{ET_{a,2}}{ET_{m,2}}\right)^{0.023} \left(\frac{ET_{a,3}}{ET_{m,3}}\right)^{0.341} \left(\frac{ET_{a,4}}{ET_{m,4}}\right)^{0.108} \tag{26}$$

Compared with the results of the relevant Reference [37] (shown in Table 2), the calculation results in this study are more appropriate. The correlation coefficient $R$ is larger than that of Reference [37], which shows that the results calibrated by AGA have higher accuracy.

### *3.3. Quantitative Assessment of Drought Loss Risk of the Study Site*

#### 3.3.1. EDRL Distribution of the Study Site

According to the wheat water production function in the study site (Formula (26)), combined with the potential and actual evapotranspiration of wheat, the yield of wheat in the region from 1976–2007 was simulated with no drought mitigation measures. Drought-related yield loss rate in each year was calculated using the linear sliding average method [29], and is shown in Figure 2.

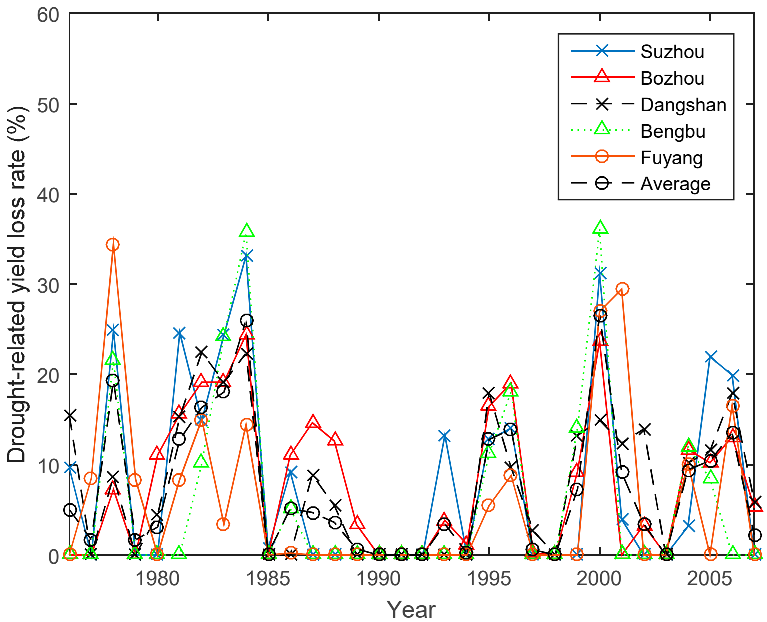


**Figure 2.** Drought-related yield loss rate of wheat in the study site, without drought mitigation measures and from 1976 to 2007.

According to the drought loss risk assessment model based on cross-validation and the information diffusion method, the frequency distribution of drought-related yield loss rate of wheat could be obtained. The mean drought-related yield loss rate in each field was calculated using Formula (20).

#### 3.3.2. Data Interpolation

In each grid of the Huaibei plain, the inverse distance-weighting method (IDW) was used to estimate the EDRL based on data from each station. According to the similarity principle, inverse distance weighting means that the smaller the distance between the interpolated point and the stations, the larger the weight is. The interpolated results could be obtained through the weighted calculation:

$$\begin{cases} Z(x_o) = \sum_{i=1}^{n} w_i Z(x_i) \\ w_i = \frac{d_{io}^{-p}}{\sum_{j=1}^{n} d_{jo}^{-p}} \end{cases} \tag{27}$$

where $Z(x_o)$ is the interpolation result of the calculated point $x_o$; $Z(x_i)$ is the station data in the point $x_i$; $w_i$ is the interpolation weight of the known point $x_i$; $d_{io}$ is the distance between points $x_o$ and $x_i$; and $p$ is the power parameter, which can be optimally estimated by obtaining the lowest root-mean-square error (RMSE) between the interpolation results and station data.

To illustrate the rationality of data interpolation, the accuracy of IDW with different observation densities was analyzed (shown in Figure 3) [38]. In this study, the average area controlled by a single station (CA) was 7.5 × $10^3$ km$^2$ per gauge and the correlation coefficients (CC) is 0.81 > 0.8 (indicating a high correlation) according to Figure 3. Compared with the Tropical Rainfall Measuring Mission (TRMM) Multi-Satellite Precipitation Analysis (TMPA) [39–41] error, the error in CC is 0.67, smaller than the value obtained by the IDW method. Moreover, the RMSE of IDW is also smaller than the TMPA error under the network density of 7.5 × $10^3$ km$^2$ per gauge. These results indicate that it was appropriate to conduct data interpolation using the data for five stations in this study.

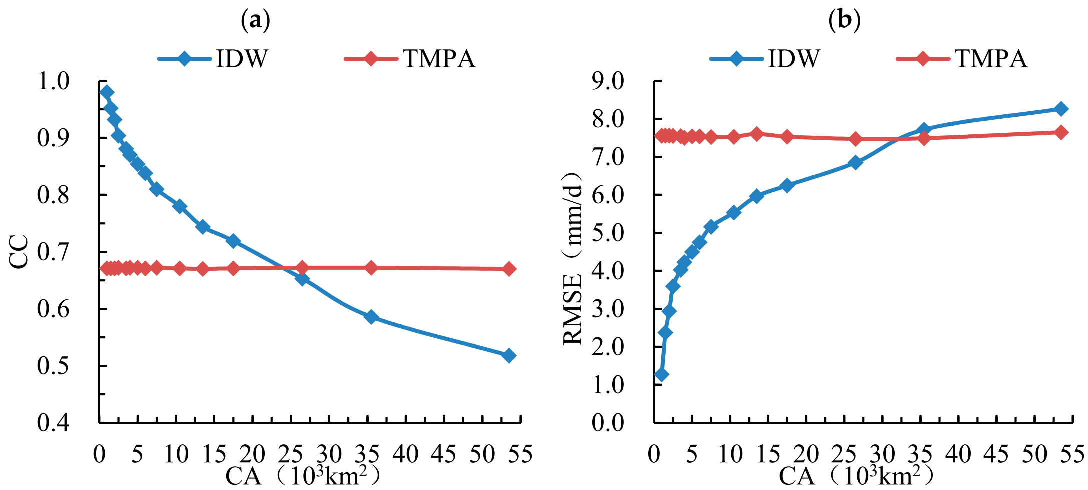


**Figure 3.** Correlation coefficients (CC) (**a**) and root-mean-square errors (RMSE) (**b**) of the standard data and two precipitation products (the inverse distance weight method (IDW) and Tropical Rainfall Measuring Mission (TRMM) Multi-Satellite Precipitation Analysis (TMPA)) for different average areas controlled by a single station. CA in the figure means the average area controlled by a single station.

#### 3.3.3. EDRM Distribution of the Study Site

The data of wheat yield in each county of the study site was collected from the drought mitigation plan and "Anhui Statistical Yearbook" [42]. The drought loss risk assessment was carried out in combination with the drought loss risk assessment model based on cross-validation and the information diffusion method; distribution diagrams of EDRM are shown in Figure 4b.

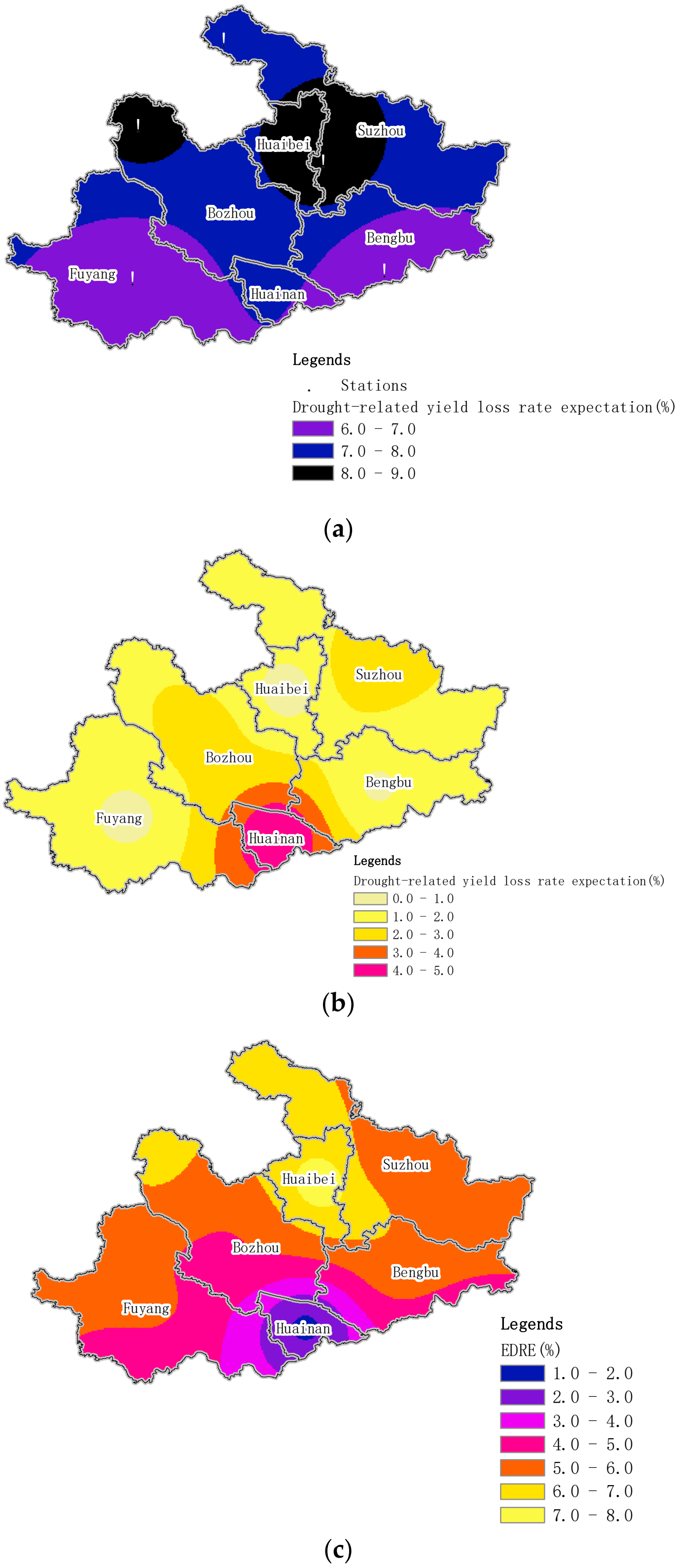


**Figure 4.** The drought-related yield loss rate expectation distribution of wheat (**a**) without drought mitigation measures (EDRL) and (**b**) under actual drought mitigation measures (EDRM); and (**c**) the expectation distribution of the drought mitigation effects index (EDRE).

### 3.4. Quantitative Assessment of Drought Mitigation Effects in the Study Site

According to the quantitative assessment model of field agricultural drought mitigation effects, the corresponding value of each point in the distribution diagram of EDRL in the study site minus EDRM (Figure 4b) based on Formula (23) is the EDRE in the distribution diagram of Figure 4c.

From Figure 4c, the low value of EDRE is concentrated on Huainan City and the eastern area of Fuyang City, and the farther the surrounding area is from the center, the higher the EDRE is. Areas with high EDRE are concentrated on Huaibei City and the Western area of Suzhou City, and the farther the surrounding area is from the center, the lower the EDRE is. In general, EDRE is higher in the Northern part of the study site, and lower in the Southern part.

## 4. Discussion

Through observation, it was found that the distribution of EDRL is very similar to that of EDRE. It can be seen from formula (23) that the EDRE is the difference between the EDRL and the EDRM, as $Ex_{A,i} \geq 0$, $Ex_{R,i} \leq Ex_{N,i}$. Accordingly, this unequal relationship makes the distribution of the EDRL impact EDRE distribution, thereby producing a very similar distribution pattern that is shown in Figure 4a,c. The drought mitigation effects refer to the effects of human mitigation to reduce losses caused by drought disasters. Therefore, the expected value $Ex_{R,i}$ of the recovered loss of drought mitigation measures cannot be larger than the expected value $Ex_{N,i}$ of drought loss without drought mitigation measures. This, in itself, has a certain rationality, because it is not necessary to plan several drought mitigation measures if the drought loss without those measures is small, and the fewer the drought mitigation measures are, the lower EDRE is. Therefore, when the EDRL is small, EDRE is also small, which shows the rationality of the measurement method of the drought mitigation effects and the consistency of the definition of the drought mitigation effect.

Figure 5 was obtained through partition statistics. As shown in Figure 5, the EDRE of Huainan is the smallest and that of Huaibei is the largest of the five cities. The EDREs of Suzhou and Bozhou are larger than the mean EDRE in the five cities. The EDREs of Bengbu and Fuyang are smaller than the mean EDRE in the five cities. To analyze the cause of this result and illustrate its rationality from the perspective of the calculation process, the small EDRE was determined to have been caused by the large EDRM and the small EDRL. From Figure 5, and by comparing Figure 4a,b, we can highlight why EDRE is highest in Huaibei: the EDRL in Huaibei City is the highest of the six cities in the Huaibei Plain, while its EDRM is the smallest. Likewise, the main reason for the high EDRE in Bozhou City and Suzhou City is the high EDRL. This is because, when EDRM is fixed, a larger EDRL will lead to a larger expectation of drought loss recovery due to drought mitigation measures, which in turn leads to a larger drought mitigation effect. Additionally, a low EDRL is the main cause for the low EDRE in Bengbu City and Fuyang City, as the EDRL in those cities is smaller than the mean EDRL of the study site. Meanwhile, the small EDRL and the largest EDRM in the study site are responsible for the lowest EDRE of Huainan City.

In general, when EDRL for a specific location is lower than the mean EDRL in the study site, a low drought mitigation effect is seen, suggesting that local drought mitigation measures do not need to be urgently increased. It is therefore necessary to identify areas where drought mitigation measures need to be increased by examining the reasons for the low drought mitigation effects.

Areas with large EDRL should not have small drought mitigation effect. Meanwhile, areas with small EDRL can have small drought mitigation effects but should not have large EDRM. Therefore, it is necessary to increase drought mitigation measures in two types of areas: (1) Areas where EDRE is low and EDRL is large, such as in the East of Bozhou City. In this area, EDRE is lower than the mean EDRE for the study site and EDRL is larger than the mean EDRL for the study site. Therefore, the area east of Bozhou City belongs to the first class of areas in which drought mitigation measures need to be increased urgently. The West of Bozhou City also belongs to this first class; and (2) the second class includes areas where the value of EDRE is low, EDRL is small but EDRM is large, such as in the west of Huainan City. This area has the lowest EDRE in the study site, and although EDRL is lower than the mean EDRL of the study site, the EDRM is the largest in the entire study area. Therefore, the area West of Huainan City belongs to the second class of areas in which drought mitigation measures should be increased urgently. The results of this calculation are helpful to guide farmland investments objectively, as well as providing a reference for the identification of key areas for drought mitigation and the allocation of drought mitigation investment in the Anhui province.

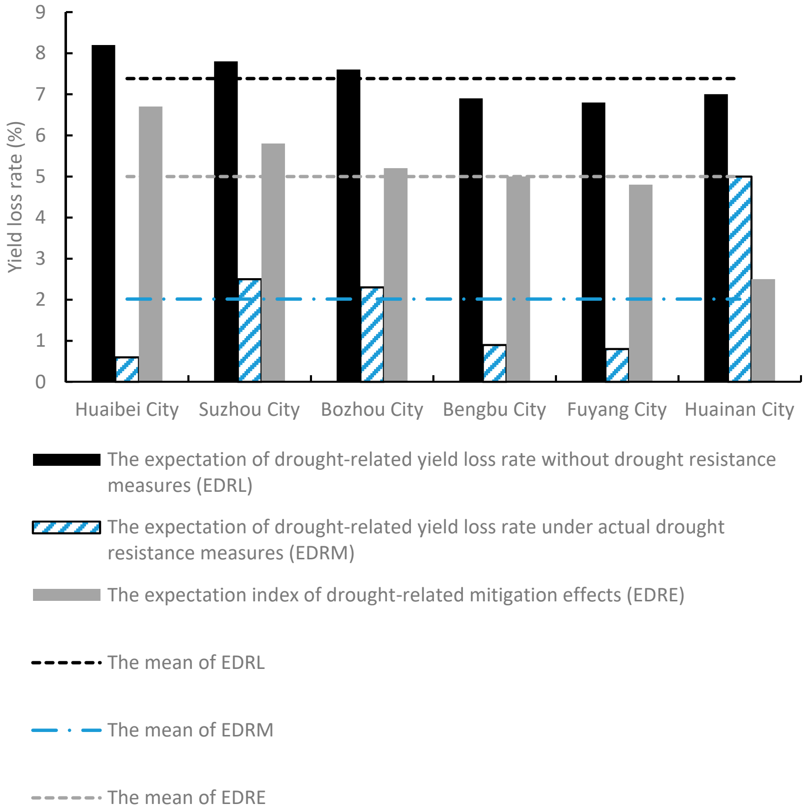


**Figure 5.** The expectation of drought-related yield loss rate without drought mitigation measures and under actual drought mitigation measures (EDRL and EDRM, respectively) and the drought mitigation effects expectation index (EDRE) in the study site.

In order to formulate specific drought mitigation measures from the factors found to influence drought mitigation effects, the CCs (R) between the index values of different influencing factors and local EDRE were calculated. Table 3 shows that the proportion of dry crops is the factor most closely correlated with local EDRE (R = 0.90), followed by temperature (R = −0.85), the proportion of water-saving irrigation area (R = 0.71), and lastly, mean annual precipitation (R = 0.64). According to the statistical theory [43], the first two factors are highly correlated with the EDRE, and the last two factors are also significantly correlated with the EDRE. Therefore, these four factors were identified as having the greatest influence on the effects of local drought mitigation, can be used to examine the reasons behind low drought mitigation effects on regional agriculture, and give concrete suggestions for drought mitigation measures. For example, as shown in Table 3, the EDRE of Huainan City is small, which may be related to the lower proportion of dry crops and of the water-saving irrigation area.

**Table 3.** Correlations between expectation of drought mitigation effects (EDRE) and its influencing factors in the study site.

| Index | Fuyang City | Bozhou City | Suzhou City | Huaibei City | Bengbu City | Huainan City | Correlation Coefficients of EDRE |
|---|---|---|---|---|---|---|---|
| EDRE (%) | 4.8 | 5.2 | 5.8 | 6.7 | 5.0 | 2.5 | 1.00 |
| Dry crop proportion | 0.91 | 0.99 | 0.97 | 0.99 | 0.70 | 0.34 | 0.90 |
| Average temperature (°C) | 15.70 | 15.54 | 15.80 | 15.59 | 16.16 | 16.75 | −0.85 |
| The proportion of water-saving irrigation area | 0.15 | 0.13 | 0.20 | 0.15 | 0.03 | 0.02 | 0.71 |
| Mean annual precipitation (mm) | 967.77 | 912.41 | 880.71 | 883.55 | 1028.91 | 987.85 | −0.64 |

According to Figure 4a and Table 3, Huaibei City and Bozhou City have a severely low EDRL and both have a very high proportion of dry crops (0.99). Bengbu City and Huainan City also have a low EDRL and both have a high proportion of dry crops (0.70 and 0.34, respectively), but are located closer to the Huaihe river. Therefore, the more severe the EDRL (i.e., the farther away from the Huaihe river), the higher the proportion of local dry crops (see the full line in Figure 6), as people in each region choose appropriate crops to adapt to the environmental conditions. For example, people far from the Huaihe River would increase the proportion of dry crops to adapt to water scarcity and people near the Huaihe River would reduce the proportion of dry crops to adapt to the abundance of water. If a large area of drought occurs in the study site, crops farther away from the Huaihe river are better adapted to this sudden water scarcity than crops near the river, and will therefore be better able to withstand drought [44]. Therefore, EDRM far from the Huaihe river (where the proportion of dry crops is high) would be smaller than that in the area close to the river (where the proportion of dry crops is low) (see dotted line in Figure 6). Consequently, the groundwater consumption in the area far from the river will be lower than that close to the river without drought mitigation measures. Furthermore, the estimation of EDRL using Formulas (1), (4), and (6) combined shows that the lower the groundwater consumption, the greater the drought loss (compared with the variation of groundwater consumption distribution, the variation of rainfall distribution in each region is negligible). Therefore, EDRL far from the river is greater than that near the river (see the solid line in Figure 6). According to the EDRE formula, the bigger the EDRL, the smaller the EDRM, and the bigger the EDRE. Therefore, the farther away the area is from the Huaihe river (where the proportion of dry crops is higher), the greater the drought mitigation effects (see the shaded portion of Figure 6). Despite the smaller proportion of dry crops in the area near the river would lead to higher irrigation area and irrigation may decrease the impact of drought, the local crops have adapted to local environment of abundant water and irrigation water cannot maintain the normal environment on the facets of surface soil moisture, temperature, and air humidity. Irrigation may also be affected by the drought and irrigation water cannot be ensured. Additionally, it cannot sustain normal crop growth in drought conditions.

To sum up, the above results illustrate the regional adaptation from the perspective of dry crop proportion, showing an inverse relationship between drought mitigation effects and local water abundance. The adaptation of drought mitigation measures can be revealed by the engineering and non-engineering measures taken according to current conditions, which will make crops farther away from the river more adaptable to water scarcity than crops closer to the river. This tendency might eventually lead to the distribution pattern observed in Figure 4c, in which EDRE is greater in areas farther away from the Huaihe river. The pattern of this distribution in Figure 4 also illustrates the rationality of the assessment model of the regional agricultural drought mitigation effects.

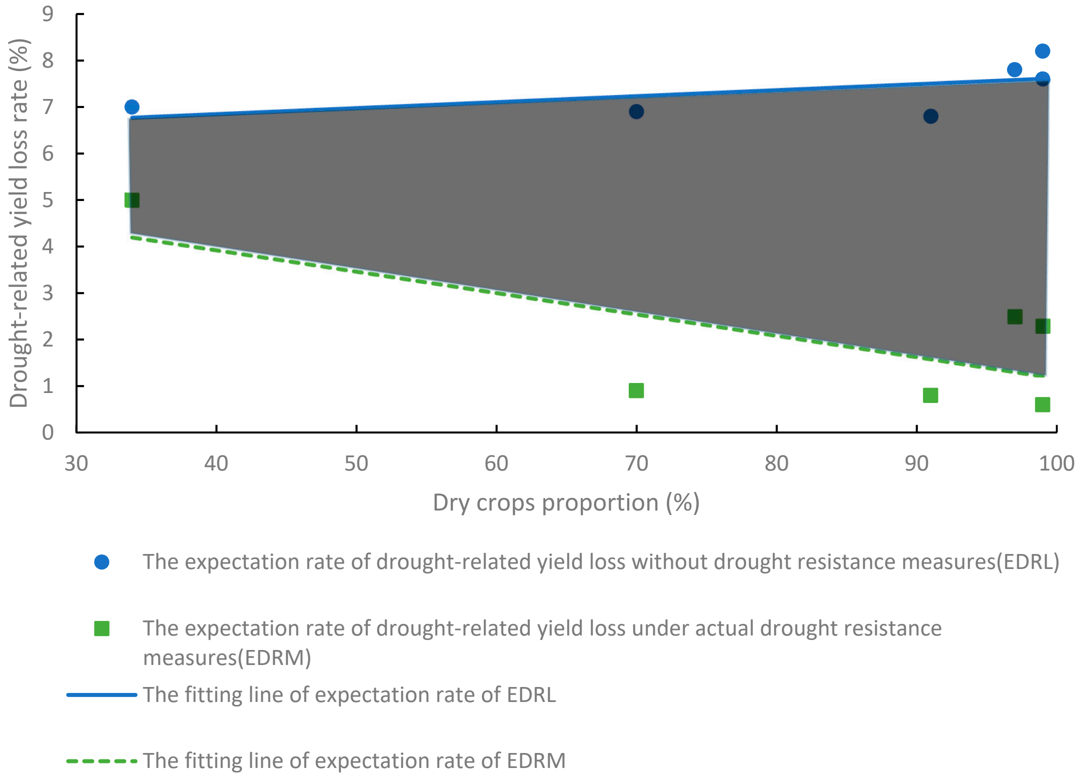


**Figure 6.** Variation in the drought-related yield loss rate without drought mitigation measures (EDRL), drought-related yield loss rate with actual drought mitigation measures (EDRM), and the expectation of drought mitigation effects (EDRE) with variation in the dry crop proportion in the study site.

## 5. Conclusions

The quantitative assessment of agricultural drought mitigation effects is an important basis for the formulation of a drought and disaster mitigation strategy, which is of great significance for scientific inquiry and for effective regional drought risk management and drought planning. In this study, the quantitative assessment model of regional agricultural drought mitigation effects was established, based on experimental and simulation data. The application of this model to wheat crops in Huaibei Plain of Anhui Province in China reveals that:

(a) According to the definitions of the drought system and drought mitigation effects, a definition of the expectation index of drought mitigation effects (EDRE) was proposed. The physical meaning of EDRE is the expected value of drought-related loss recovery through drought mitigation measures. The EDRE distribution diagram could be obtained based on the expectation distribution diagram of drought-related yield loss rate without drought mitigation measures (EDRL) and under drought mitigation measures (EDRM). The results show that the effects of drought mitigation are small in the South and large in the North of the study site.

(b) The distribution pattern of EDRE is similar to that of the EDRL, which is related to $Ex_{R,i} \leq Ex_{N,i}$. At the same time, the lower EDRE is mainly due to a higher EDRM and a lower EDRL. Areas where EDRE is low and the EDRL is high, or where EDRE is low and the EDRM is high require urgent drought mitigation measures. Therefore, the East and West of Bozhou City and the West of Huainan City urgently need to increase drought mitigation measures.

(c) Through a correlation analysis of the drought mitigation effect and the factors influencing it, drought mitigation measures (such as increasing the proportion of dry crops and the water-saving irrigation area) were identified. Additionally, the local adaptation of drought mitigation measures leads to an inverse relationship between the drought mitigation effects and local water abundance, forming a spatial distribution pattern in which the areas farther away from the mainstream of the

Huaihe River exhibit greater drought mitigation effects. This also shows the rationality of the assessment model of regional agricultural drought mitigation effects.

**Author Contributions:** Data curation, S.J.; Investigation, S.J.; Methodology, S.J., Y.Z. (Yuliang Zhang), and Y.Z. (Yuliang Zhou); Resources, S.N. and Y.Z. (Yuliang Zhou); Supervision, J.J.; Validation, Y.Z. (Yuliang Zhang); Writing—original draft, Y.Z. (Yuliang Zhang); Writing—review & editing, J.J. and Z.W.

**Funding:** This research was funded by the National Key Research and Development Program of China (grant No. 2017YFC1502405), the National Natural Science Foundation of China (grant Nos. 51579059, 51709071, 51779067), and Postgraduate Research & Practice Innovation Program of Jiangsu Province (Grant No. SJKY19_0471).

**Acknowledgments:** The authors thank Xiuqing Cao, Hongwei Yuan, Jiwei Yang, and other staffs from Anhui and Huaihe River Institute of Hydraulic Research, China. We also thank the anonymous reviewers for their suggestions. In addition, we thank Xueyang Zhang from Space Engineering University (China) and Editage for the help of English editing.

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

## References

1. Leslie Lyons, D.; Debra, P.; Jacobi, J.H.; Hornberger, G.M. Drought planning and management: using high spatial resolution as part of the solution. *Environ. Sci. Technol.* **2015**, *49*, 2639–2647.
2. Zhang, Q.; Han, L.; Zhang, L.; Wang, J. Analysis on the character and management strategy of drought disaster and risk under the climatic warming. *Adv. Earth Sci.* **2014**, *2*, 6709–6713. (In Chinese)
3. Qu, Y.; Gao, H.; Lv, J.; Su, Z.; Cheng, X.; Sun, H. Agricultural drought disaster risk assessment in China based on the regional disaster system theory. *J. Hydraul. Eng.* **2015**, *46*, 908–917. (In Chinese)
4. Haro, D.; Solera, A.; Paredes, J.; Andreu, J. Methodology for drought risk assessment in within-year regulated reservoir systems. Application to the Orbigo River System (Spain). *Water. Resour. Manag.* **2014**, *28*, 3801–3814. [CrossRef]
5. Qu, Y.; Li, J.; Lyu, J.; Su, Z.; Qiu, B.; Li, A. A quantitative framework for assessing drought disaster risk and key techniques. *Adv. Water Sci.* **2014**, *25*, 297–304. (In Chinese)
6. Chen, H.; Wang, J.X.; Huang, J.K. Evaluation of drought resisting effects of rural irrigation infrastructure: based on empirical study in seven provinces in China. *J. Nat. Resour.* **2012**, *27*, 1656–1665. (In Chinese)
7. Chen, C.; Sa, J.; Yan, K.; Du, Y.; Mu, L. Effect of different cultivation measures on drought resistance of oats. *Jiang Agric. Sci.* **2016**, *44*, 171–173. (In Chinese)
8. Xing, S.P. Drought-resistant effect of special-processing-purpose Ganhua 92-01 peanut under different tilths. *J. Anhui Agric. Sci.* **2010**, *38*, 14903–14904, 14943. (In Chinese)
9. Song, T.Q.; Xiao, R.L.; Peng, W.X.; Yang, Z.J.; Sheng Hua, L.I.; Xiao, K.C.; Teng, H.H. Upgrading soil water and other ecological effects of intercropping white clover in tea plantation in subtropical hilly region. *Agric. Res. Arid Area* **2006**, *24*, 39–43. (In Chinese)
10. Sun, G.; Pei, Z.; Tu, Y.; Kong, J.; Zhang, X. Drought-resistant effect of different drought-resistant technology combinations on tabulaeformis of mine. *Jiang Agric. Sci.* **2015**, *43*, 360–363. (In Chinese)
11. Asgharipour, M.R.; Heidari, M. Effect of potassium supply on drought resistance in sorghum: Plant growth and macronutrient content. *Pak. J. Agric. Sci.* **2011**, *48*, 197–204.
12. Hao, L.L.; Wang, X.Q.; Zhang, X.R.; Zhu, Q.Z. Effect of chitosan on growth and drought resistance of wheat seedlings under drought stress. *Resour. De Mark.* **2014**, *30*, 908–909, 1005. (In Chinese)
13. Yang, Y.; Chang, D.; Wang, Y.; Zhang, F. Effect of Methyl Jasmonate(MeJA)on enhancing drought resistance of cotton. *Acta Agric. Bore Sin.* **2016**, *25*, 1333–1341. (In Chinese)
14. Yuan, Z.; Wang, C.; Li, S.; Li, X.; Tai, F. Effects of different plant hormones or PEG seed soaking on maize resis. *Can. J. Plant. Sci.* **2014**, *94*, 1491–1499. [CrossRef]
15. Kai, R.L.; Feng, C.H. Effects of brassinolide on drought resistance of Xanthoceras sorbifolia seedlings under water stress. *Acta Physiol. Plant* **2011**, *33*, 1293–1300.
16. Li, K.R.; Wang, H.H.; Han, G.; Wang, Q.J.; Fan, J. Effects of brassinolide on the survival, growth and drought resistance of Robinia pseudoacacia seedlings under water-stress. *New For.* **2008**, *35*, 255–266. [CrossRef]
17. Qiu, Z.B.; Liu, X.; Tian, X.J.; Yue, M. Effects of $CO_2$ laser pretreatment on drought stress resistance in wheat. *J. Photochem. Photobiol. B* **2008**, *90*, 17–25. [CrossRef] [PubMed]

18. Li, G.; Liu, X. *Climate and Wheat Meteorological Disaster of Huaibei Plain*; China Agricultural Science and Technology Press: Beijing, China, 1999. (In Chinese)
19. Wang, Z.; Zhang, Q.; Li, R. *Hydrological Experiment Research in Huaibei Plain*; University of Science and Technology of China Press: Hefei, China, 2011. (In Chinese)
20. Allen, R.; Pereira, L.; Raes, D.; Smith, M. Crop evapotranspiration guidelines for computing crop water requirements. *Fao Irrig. Drain. Pap.* **1998**, *300*, 24.
21. Yang, X.B. Research progress on the utilization of shallow groundwater under the planting conditions of crops. *J. Anhui Agric. Sci.* **2008**, *36*, 9649–9650. (In Chinese)
22. Wang, X.; Hou, H. Study on shallow groundwater evaporation laws of crops and bare soil. *J. Hydroelectr. Eng.* **2008**, *27*, 60–65. (In Chinese)
23. Zhou, D.; Shen, Y.J.; Chen, Y.N.; Guo, Y.; Zhang, B. Estimation of ecological water requirement of desert vegetation in the arid region of Northwest China. *Chin. J. Ecol.* **2015**, *34*, 670–680. (In Chinese)
24. Kang, S.; Cai, H. *Agricultural Water Management Science*; China Agriculture Press: Beijing, China, 1996. (In Chinese)
25. Zhan, D.; Xu, X.; Chen, Y. *Engineering Hydrology*; China Water Power Press: Beijing, China, 2010. (In Chinese)
26. Qi, S.; Li, Z.; Gong, Y. Evaluating crop water requirements and crop coefficients for three vegetables based on field water budget. *J. China Agric. Univ.* **2002**, *7*, 71–76. (In Chinese)
27. Guo, Y. *Irrigation and Drainage Engineering*; China Water & Power Press: Beijing, China, 1997. (In Chinese)
28. Xue, C.Y.; Huo, Z.G.; Li, S.K.; Ye, C.L. Risk assessment of drought and yield losses of winter wheat in the northern part of North China. *J. Nat. Disasters* **2003**, *12*, 131–139. (In Chinese)
29. Zhang, Y.; Jiang, S.; Jin, J.; Zhou, Y.; Zhang, M. Drought loss risk assessment model based on cross-validation and information diffusion. *South-to-North Water Transf. Water Sci. Technol.* **2016**, *14*, 175–183. (In Chinese)
30. Zhao, S. A preliminary study on the spatial and temporal scales of natural disaster risk analysis. *J. Catastrophol.* **2012**, *27*, 18. (In Chinese)
31. Li, N.; Wen, Y.; Xie, W.; Zhou, Y.; Liu, X. Comparative study on different risk zonings of drought about wheat in Anhui Province. *J. Nat. Disasters* **2012**, *21*, 173–179. (In Chinese)
32. Jin, J.; Li, J.; Zhou, Y.; Fei, Z.; Jiang, S.; Yuan, X.; He, J. Research on the theoretical framework of drought risk assessment. *J. Catastrophol.* **2014**, *29*, 1–10. (In Chinese)
33. Jin, J.L.; Yuan, C.Y.; Jiang, S.M.; Hu, X.U. Assessment of drought resistance ability for pond and retaining dam irrigated area of Jianghuai hilly area based on water supply and demand balance analysis. *J. Hydraul. Eng.* **2013**, *44*, 534–541. (In Chinese)
34. Li, C.; Rong, F.; Feng, M.; Li, Q. Analysis of agricultural drought resistance level in Shanxi Province. *Shanxi Hydrotech.* **1995**, *2*, 1–6. (In Chinese)
35. Liu, G. *Agricultural Quick Reference Manual*; Chemical Industry Press: Beijing, China, 2008. (In Chinese)
36. The Ministry of Water Resources of the People's Republic of China. *Irrigation Experiment Standard*; China Water & Power Press: Beijing, China, 2004; Volume SL 13-2004. (In Chinese)
37. Anhui Huaihe River Institute of Hydraulic Research. *Drought Test Report on Grain Crops in 2012*; Anhui & Huaihe River Institute of Hydraulic Research: Hefei, China, 2012. (In Chinese)
38. Wu, Z.; Zhang, Y.; Sun, Z.; Lin, Q.; He, H. Improvement of a combination of TMPA (or IMERG) and ground-based precipitation and application to a typical region of the East China Plain. *Sci. Total. Environ.* **2018**, *640–641*, 1165–1175. [CrossRef] [PubMed]
39. Kummerow, C.; Barnes, W.; Kozu, T.; Shiue, J.; Simpson, J. The Tropical Rainfall Measuring Mission (TRMM) sensor package. *J. Atmos. Ocean. Technol.* **1998**, *15*, 809–817. [CrossRef]
40. Huffman, G.J.; Bolvin, D.T.; Nelkin, E.J.; Wolff, D.B.; Adler, R.F.; Gu, G.; Hong, Y.; Bowman, K.P.; Stocker, E.F. The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. *J. Hydrometeorol.* **2007**, *8*, 38–55. [CrossRef]
41. Huffman, G.J.; Bolvin, D.T. *Real-Time TRMM Multi-Satellite Precipitation Analysis Data Set Documentation*; TRMM 3B4XRT_doc_V7; National Aeronautics and Space Administration (NASA): Washington, DC, USA, 2017; p. 48.
42. Bureau of Statistics of Anhui. *Anhui Statistical Yearbook*; China Statistics Press: Beijing, China, 2000–2013. (In Chinese)

43. Fang, Q. *Statistics*; Northeast Normal University Press: Changchun, China, 2011. (In Chinese)
44. Jin, J.; Song, Z.; Cui, Y.; Zhou, Y.; Jiang, S.; He, J. Research progress on the key technologies of drought risk assessment and control. *J. Hydraul. Eng.* **2016**, *47*, 398–412. (In Chinese)