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# Study on the Dynamic Low Limit of Irrigation for Winter Wheat

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**Abstract.** The concept of dynamic irrigation low limit (DILL) was proposed and the determination method of DILL was given based on crop-water model. The parameters of the crop-water model were calibrated with winter wheat experimental data of 2008 and 2009. The optimal irrigation scheduling of five typical years under different irrigation water supply were determined, which resulted in 58 groups of data on the average soil moisture content of main root zone (0-60cm) before an irrigation, the corresponding irrigation time, and water supply. The results showed that, the crop yield under the irrigation times of 3 and 2 increased by 7.42% and 5.62% averaged from 2009 to 2013, and the economic benefit increased by 7.64% and 7.24% than those under the empirical irrigation practices, respectively. The irrigation forecast based on DILL provides an important method to implement and dynamically correct optimal irrigation scheduling under limited water supply.

**Keywords:** Irrigation scheduling · Irrigation low limit · Irrigation forecast · Crop yield · Irrigation and fertilization

## 1 Introduction

The annual precipitation change in arid and semi-arid areas is larger, and there is always a part of year that water supply cannot meet the crop requirement. Nearly a quarter of the certain year will be reduction because of not get enough water at the designed irrigation guarantee rate of 75%. The shortage of irrigation water in North China is very serious. For Haihe River basin and the Yellow River basin is 10.8 and 4.8 billion m<sup>3</sup> and water of shortage per unit area is 1400 and 910 m<sup>3</sup>/hm<sup>2</sup>, respectively [1]. Therefore, there will be more years with crop yield reduction because irrigation water supply cannot meet the irrigation requirement.

Taking the limited irrigation water applied to water-sensitive stage so that to achieve maximum output and efficiency [2]. Firstly, people use the field experiment of irrigation system [3, 4] to analysis and determine the optimal irrigation time and irrigation quota, and then optimization algorithm is used to determine the optimal irrigation schedule, such as optimized the limit water irrigation schedule for a specific year [5-11]. Further, considering the stochastic change of the precipitation and potential evaporation, stochastic dynamic programming method was applied to analysis and given the optimal irrigation schedule [12-15]. However, the optimal irrigation schedule is optimal in terms of a series of meteorological data, and it is generally not optimal for a particular year of the series. The analysis based on field experiment or using the optimization theory for determining the optimal irrigation schedule can only applies to irrigation water plan at the beginning of crop growing season and cannot be used for real-time correction of the irrigation plan.

The core of real-time correction of the irrigation water plan is to determine the reasonable irrigation low limit value, such as the traditional suitable irrigation low limit value [16]

and water-saving irrigation's low limit value [17]. The irrigation forecast according to the suitable irrigation low limit value can realize timely and adequate irrigation to obtain maximum yield, and avoid excessive of water supply [18-23]. On the basis of water saving irrigation's low limit value, high water productivity can be obtained; using economic irrigation low limit value for real-time correction of irrigation water plan, can make the largest irrigation benefit per unit area [24-26].

Therefore, the relationship between irrigation limit value and crop growth under limited water supply were analyzed in this study. Determining irrigation low limit value is not only related to crop growth and development, but also changes with water supply, so it is called dynamic water limit. The proposed dynamic irrigation low limit can provide a new method for irrigation forecast and real-time correction of irrigation plan with limited water supply.

## 2 The method of Determination Dynamic Irrigation Low Limit

### 2.1 Crop Water Model

Crop water model is expressed by the relationship of crop yield and irrigation fertilization generated by coupling the crop growth model, crop evapotranspiration model, and soil hydrothermal solute transport model under the influence of evapotranspiration. Here the P123 crop growth model given by Driessen [27] was used to calculating photosynthetic product

$$P_{di} = P_{dmi} \cdot FW_i \cdot FN_i \quad (1)$$

Where  $P_{di}$  is the daily amount of photosynthesis production of crops with water and nutrient stresses at day  $i$ , kgMD/(hm<sup>2</sup>.d);  $P_{dmi}$  is the daily amount of photosynthesis production of crops without water and nutrient stresses, kgMD/(hm<sup>2</sup>.d);  $FW_i$  and  $FN_i$  are water stress coefficient and nutrient stress coefficient.

$P_{dmi}$  in Equation (1) can be calculated by

$$P_{dmi} = F_{gci} \cdot Y_g \cdot 30 / 4 \quad (2)$$

Where  $F_{gci}$  is the daily obturation reference to crop's total carbon dioxide absorption rate, kg/ hm<sup>2</sup>/d is calculated by the formula given by P.M. Driessen. 30/44 is the ratio of the molecular weight of CH<sub>2</sub>O and CO<sub>2</sub>;  $Y_g$  is photosynthetic product conversion efficiency [28]. After obtained the  $P_{di}$ , the daily increment of root, stem, leaf, seed, and the accumulative dry weight can be calculated. The dry weight of seed at the time of harvest is the crop yield.

Water stress coefficient and nutrient stress coefficient were calculated by the following equations [29]:

$$FW_i = \left( \frac{T_{ai}}{T_{pi}} \right)^\sigma \quad 0 < FW_i \leq 1 \quad (3)$$

$$FN_i = \left( R_{ipyN}(t) \right)^\lambda \quad 0 < FN_i \leq 1 \quad (4)$$

$$R_{ipyN}(t) = \min[1, P_N(t) / P_{critN}(t)] \quad (5)$$

Where  $T_{ai}$  is the daily actual crop transpiration under water stress conditions, mm/d.  $T_{pi}$  is the potential transpiration of crops, mm/d.  $\sigma$  is the water stress index, reflects the degree of sensitivity of the impact water deficit on crop growth.  $\lambda$  is the nutrition stress index, reflects the influence of nutrient deficiency on crop growth and yield.  $P_N(t)$  is the crop plant nitrogen content at  $t$  moment.  $P_{critN}(t)$  is the critical nitrogen content of crop plants at

time  $t$ , defined as the required minimum nitrogen content without nitrogen stress for crop growth, %.

The actual transpiration, potential transpiration, and plant nitrogen content in formula (3) and formula (4) can be obtained by dynamic simulation of soil water, heat and nitrogen in the crop root layer. The soil moisture dynamic simulation was based on the one-dimensional Richards equation for soil water flow[30], where the root water uptake and heat flow equation adopted the calculation methods given by Kang Shaozhong(1994) [31]and Shang Songhao(2009), respectively [32].

There is less precipitation in winter wheat growing season, and little runoff is generated in the process of precipitation infiltration. In addition, the conceptual method is adopted due to precipitation irrigation process much shorter than the evapotranspiration process, that is, the infiltration of surface soil water supply the upper soil first and will migrate downward only when the upper soil moisture content exceeds the field capacity [33].

The saturation and soil water characteristic curve were used to calculate unsaturated soil hydraulic conductivity and water diffusivity in the process of soil moisture movement simulation [32, 34, 40] considering the influence of soil temperature changes [34]. Soil nitrogen simulation was based on the coupled equations with the dependent variables of ammonium nitrogen and nitrate [29-35], nitrogen of the hydrodynamic dispersion coefficient is divided into two parts, flow rate and diffusion rate for calculation [36].

Using implicit difference method and iterative method, the time step was 1440 minutes, the length step is 20 cm. Meteorological factors, such as daily air temperature, humidity, adopted the mean value without considering its diurnal variation. The calculation depth is 200-cm. Iterative calculation twice before and after the calculation of soil moisture content. The gentle nitrate content allowed error is 0.01, the number of iterative calculation depends on if there is precipitation and irrigation, no precipitation and irrigation, the number of iterations is small, have larger precipitation and irrigation, the number of iterations is larger, but the maximum times was no more than 5.

## 2.2 Optimizing and Solving Irrigation Schedule under Different Water Supply Condition

### 2.2.1 Optimization Model

In the irrigation schedule optimization does not consider the change of the irrigation quota, only for a given irrigation water supply, determine the optimal irrigation time. Because of the complexity of the crop water requirement, yield calculation. Irrigation schedule optimization in this study belongs to nonlinear programming problem, the mathematical model are as follows.

Objective function, obtain the biggest benefit per unit area

$$\max B = P_c \cdot y - P_w \cdot m \cdot J / \eta / 1.5 - C_0 \quad (6)$$

Constraint condition, mainly by irrigation time limit

$$t_1 \leq x_1 < x_2, x_{j-1} \leq x_j < x_{j+1}, x_{J-1} \leq x_J < t_m - t_2 \quad (7)$$

Where  $B$  is the net-income of per unit area, RMB/hm<sup>2</sup>;  $y$  is the crop yield, kg/hm<sup>2</sup>.  $t_1$  is the winter wheat tiller stage, expressed in the number of days from sowing date, d.  $t_2$  is the day stop irrigation, d;  $t_m$  is the number of days in the growth season, d;  $x_j$  is the irrigation temporal at one time; 1.5 is the unit conversion coefficient.  $J$  is the irrigation frequency from returning green stage to harvest;  $m$  is the irrigation quota, mm, to simplify the calculation, irrigation quota in the growth season does not change;  $\eta$  is the utilization coefficient of irrigation water.  $P_c$  and  $P_w$  are respectively represent winter wheat product price (RMB/kg) and irrigation water price (RMB/m<sup>3</sup>), considering the irrigation labor cost in the irrigation water price.  $C_0$  is the irrigation water of other agricultural inputs, RMB/hm<sup>2</sup>, not change with irrigation water.

## 2.2.2 Optimization of Irrigation Schedule

For a typical year, assuming irrigation water for one time, through optimizing calculation, can determine the optimal irrigation time; assume that irrigation water is for 2 times, 3 times in turn, computed the optimized irrigation time, until the benefits began to decrease. It can determine the typical years under the condition of different irrigation water supply optimization irrigation time, one of the biggest corresponding benefit irrigation frequency and irrigation quota and irrigation time for the system is economic irrigation.

## 2.3 Determination of Dynamic Water Low Limit Value

Different from the traditional suitable low limit irrigation, dynamic irrigation low limit is not directly through field experiment, but based on the optimized irrigation schedule obtained by statistical analysis. Based on the optimized irrigation schedule in the main root area (0 to 60 cm) an average soil content as irrigation low limit value before every irrigation. Establish the relationship between dynamic water low limit and the corresponding irrigation time and later supply amount (the sum of irrigation water and precipitation), see the formula (8), through the regression analysis to determine the type of the parameter.

$$\theta_l = a_0 + a_1 t_r^m + a_2 W^n + a_3 W^p t_r^q \quad (8)$$

Where  $\theta_l$  is the dynamic irrigation low limit value, expressed by average soil moisture content at the soil depth of 0-60cm,  $\text{cm}^3/\text{cm}^3$ ;  $t_r$  is the relative growth time,  $t_r = t/t_m$ ;  $t$  is from the sowed day since the date of seeding growth;  $W$  is the water supply, mm. Its value is equal to the sum of available irrigation water and precipitation from irrigation time to harvesting the crops, that is

$$W = \sum_{t=t_j}^{t_m} (M + P)$$

$t_j$  is irrigation water of crop growth period at one time;  $m$ ,  $n$ ,  $p$  and  $q$  is undetermined index;  $a_0$ ,  $a_1$ ,  $a_2$  and  $a_3$  is undetermined coefficients.

## 3 Sample calculation

This research using two years' test data of winter wheat in Tianjin Agriculture University's irrigation testing site during 2008 and 2009, calibrate and inspect the model parameters.

### 3.1 Texting Survey

Tianjin Agricultural University irrigation testing site is located in Da Liu Tan village, Yangliuqing town, Tianjin City, east longitude  $116^{\circ}57'$ , north latitude  $39^{\circ}08'$  sea-level elevation 5.49m. Annual meaning temperature is 11.6 degrees, annual frost-free period 203d, sunshine duration 2810.4h. The Precipitation is 586.1mm from total area of experimental field  $1\text{hm}^2$ . Amplitude of ground water level is between 4.7m to 2.6m. The characteristics of soil profile are obvious. With increasing depth in soil: the loam, sandy loam, clay sand inclusion, clay loam soil, Layered soil bulk density, soil water characteristics and field capacity in Table.1. The water characteristic retention curves have been established by the centrifuge test and use the van Genuchten formula [37] to imitate. The testing site has an  $80\text{m}^3$  reservoir. The water source of irrigation is groundwater, the plastic cement tube has been used in farmland irrigation, and water is measured by water meter.

**Table.1.** Experimental field profile soil texture and soil moisture characteristic parameters

| Soil depth/cm | Soil texture        | $\theta_s/cm^3/cm^3$ | $\theta_r/cm^3/cm^3$ | $\alpha$ | n     | $K_s/cm/d$ | Soil bulk density /g/cm <sup>3</sup> | Field Capacity/cm <sup>3</sup> /cm <sup>3</sup> |
|---------------|---------------------|----------------------|----------------------|----------|-------|------------|--------------------------------------|---|
| 0-30          | loam                | 0.362                | 0.066                | 0.0116   | 1.234 | 7.2        | 1.41                                 | 0.317   |
| 30-95         | Sandy loam          | 0.486                | 0.063                | 0.0026   | 1.699 | 21.0       | 1.42                                 | 0.385   |
| 95-135        | clay sand inclusion | 0.471                | 0.077                | 0.0030   | 1.327 | 1.4        | 1.47                                 | 0.382   |
| 135-160       | clay loam soil      | 0.509                | 0.137                | 0.0013   | 1.346 | 1.2        | 1.48                                 | 0.419   |

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{(1 + |\alpha h|^n)^m} \quad (9)$$

$$K(h) = K_s S_e^l \left( 1 - S_e^m \right)^{2m} \quad (10)$$

Where  $\theta$  is the soil moisture content, cm<sup>3</sup>/cm<sup>3</sup>;  $\theta_s$  is the saturated water capacity, cm<sup>3</sup>/cm<sup>3</sup>;  $\theta_r$  is the soil residual water content, cm<sup>3</sup>/cm<sup>3</sup>;  $h$  is the soil water suction;  $K(h)$  is the unsaturated soil hydraulic conductivity, cm/d;  $K_s$  is the soil saturated conductivity, cm/min;  $S_e$  is the saturation,  $S_e = (\theta - \theta_r) / (\theta_s - \theta_r)$ ;  $l$  is the Space correlation parameters[39-41]. Assumed as a constant 0.5;  $m=1-1/n$ ;  $\alpha$  and  $n$  are undetermined parameters.

Five treatments completed dry matter weight testing accumulating process of root, stem, leaf and grain the corresponding processing design are shown in table 2 by using field plot test each plot was 4m×10m, each treatment set three repetition. The main observation items were leaf dry weight and leaf area, stem weight and plant height, grain weight, root weight and root distribution, seedling number or spike number, soil water content, soil ammonium nitrogen and nitrate nitrogen content.

**Table.2.** The winter wheat irrigation and fertilizer treatments in 2008 and 2009

| Transacti on Number | process context | Quantity of base fertilizer/kg/hm <sup>2</sup> | Quantity of additional fertiliz er /kg/hm <sup>2</sup> | Irrigation amount /m <sup>3</sup> /hm <sup>2</sup> | irrigation requirement/m <sup>3</sup> /hm <sup>2</sup> |          |        |          | gaging pipenumber |
|---------------------|-----------------|--|--|--|--|----------|--------|----------|-------------------|
|                     |                 |  |  |  | Hiber nate   | Jointing | eaming | grouting |                   |
| 1                   | H180            | 750  | 225  | 1800   | 600  | 600      | 600    | 600      | 1                 |
| 2                   | M120            | 450  | 150  | 1200   |  | 600      |        | 600      | 5                 |
| 3                   | M0              | 450  | 150  | 0  |  |          |        |          | 6                 |
| 4                   | 0120            | 0  | 0  | 1200   |  | 600      |        | 600      | 9                 |
| 5                   | O               | 0  | 0  | 0  |  |          |        |          | 8                 |

Attention: base fertilizer, compound fertilizer, drilling, urea with jointing water. In the table, H, M and O were present three different levels at high levels and medium level and not fertilize. Relevant quantities of base fertilizer are 750,450 and 0 kg/hm<sup>2</sup>. The quantities of drilling are 225, 150 and 0 kg/hm<sup>2</sup>.

### 3.2 Valuing and Calibrating of Model Parameter

Sequence determined according to the simulation calculation process and model parameter. Firstly, the parameters of crop evapotranspiration and soil water movement.

The transportation and transformation parameters of nitrogen and other nutrients in soil were followed. The third is the simulation parameters of crop growth processing.

### 3.2.1 Dynamics Simulation of Soil Moisture Parameters

Soil moisture dynamic simulation parameters in crop growth period include parameters of soil water characteristic and the related parameters of crop evaporation transpiration by simulating. Soil water characteristic parameters include soil water characteristic curve, saturated hydraulic conductivity, field capacity etc. Stratified sampling was according to the structure of soil profile of the actual testing data (table1).

The main parameters of crop are relevant parameters of crop evapotranspiration simulation. The reference crop water requirement of winter wheat before and after overwintering stages was smaller. Therefore, the winter wheat combined before overwintering stage and during the overwintering stages and initial growth stage. Thus, the growth period of winter wheat was divided into four stages: initial growth stage, rapid development stage, middle stage and mature stage. Crop coefficient is the initial value to adjust the calculations. In 2009, treat one with high irrigation and treatment 5 with non-irrigation.

The objective function is to minimize error sum of squares between the simulated and measured values of the soil water content by using optimization method so as to solve crop coefficients of winter wheat (table3).

At the same time, during the adjustment process, the parameters of the root water up taking model were also verified. Simulated values of soil water content in the corresponding layered soil and the coefficients of correlation  $R^2=0.8430$  average relative error  $ARE=13.4\%$  the number of samples is 396.

**Table.3.** The crop coefficients for winter wheat

| Project             | Initial growth stage | Fast growing period | Mid growth stage             | mature period                    |
|---------------------|----------------------|---------------------|------------------------------|----------------------------------|
| Name of birth stage | Sowing to revival    | Revival to booting  | Booting to end grain filling | End grain filling to the harvest |
| Days of birth/ d    | 146                  | 41                  | 40                           | 21                               |
| Crop coefficient Kc | 0.38                 | 0.38~1.19           | 1.19                         | 1.19~0.44                        |

Attention: In growing stages using day after sowing to present. Winter wheat was sowed in October 6, 2008.

### 3.2.2 Dynamic Simulation of Soil Nitrogen Parameters

Parameters of nitrogen transporting and transformation in soil include hydrodynamic dispersion coefficient, nitrogen nitrification, mineralization, volatilization, biological uptake etc. Which also include the soil temperature and soil moisture content on nitrogen transport and transformation process. Parameters of nitrogen dynamic simulation are more. This study mainly analyzes the value [30] based on the value, greatly influenced parameter by soil is analyzed and adjusting calculated. The goal of adjustment is that simulated and measured values of layered soil nitrate nitrogen concentration have the minimum sum of squared errors. Basing on the treatment of one and the treatment of 5 with no fertilizer and no fertilizer respectively in the year 2009, parameters of nitrogen migration and transformation were analyzed and determined. Results are shown in table 4. The corresponding correlation coefficient of simulated and measured values of layered soil nitrate nitrogen concentration  $R^2 = 0.7664$ . Average relative error  $ARE = 25.6\%$ , the number of samples is 112.

**Table.4.** The parameters of nitrogen transport and transformation model

| Parameter | hydrodynamic dispersion coefficient | adsorption coefficient | Km/min <sup>-1</sup> mineralization | Nitrification rate Kn/min <sup>-1</sup> | evaporation rate Kv/min <sup>-1</sup> | Root nitrogen absorption |
|-----------|-------------------------------------|------------------------|-------------------------------------|---|---------------------------------------|--------------------------|
|-----------|-------------------------------------|------------------------|-------------------------------------|---|---------------------------------------|--------------------------|

| Name             | $\mu/\text{cm}$ | $\tau_a$ | rate |                      |                       |                       | coefficient Kr |
|------------------|-----------------|----------|------|----------------------|-----------------------|-----------------------|----------------|
| parameter values | 5               | 0.5      | 0.17 | $1.3 \times 10^{-8}$ | $3.64 \times 10^{-5}$ | $1.48 \times 10^{-4}$ | 1              |

### 3.3 Calibration and Testing of Crop Water Model Parameters

The parameters that crop water model need to be calibrated include the efficiency of photosynthetic product conversion and related parameters in the calculation of the distribution.

#### 3.3.1 Relevant Parameters of Photosynthetic Product in Distribution Calculation

Relevant parameters of calculation of distribution photosynthetic products include stem and leaf, stem, coefficient of root cap growth balance [29], such as using dry matter weight dynamic test data of winter wheat root, stem, leaf and grain with high water and high fertilizer treatment in the year 2009 with relative growth rate as the independent variable and regression analysis. 't' is concluded that the growth of the three balance coefficient charge law:

$$K_{sl} = a_{sl} \cdot RDS^{b_{sl}} \quad (11)$$

$$K_{se} = \frac{c_{se}}{1 + a_{se} e^{b_{se}(RDS - RDS_g)}} \quad (12)$$

$$A = R_m(\beta_e \cdot f_e + \beta_s \cdot (1 - f_e)) \quad (13)$$

Where

$$R_m = a_m RDS^{b_m} \quad (14)$$

Where  $K_{sl}$ ,  $K_{se}$  and  $A$  is the stem and leaf, stem and grain growth of root and shoot balance coefficient, these are function of crop growth and development time. Related to crop variety

$$RDS = \sum_{t=1}^t (T_{at} / T_0) \quad (15)$$

$RDS$  is the relative growth rate[27].

Where  $T_{at}$  for the sowing date( $t = 1$ )calculating effective accumulated temperature of winter wheat since the t day, °C;  $T_0$  is the whole growth period of effective accumulated temperature of winter wheat °C;  $R_m$  is the root shoot ratio under normal growth conditions of winter wheat;  $\beta_e$  and  $\beta_s$  are critical nitrogen content of winter wheat grain and straw (including roots, stems, leaves), respectively. kg/kg, values were 0.01 and 0.004[27];  $f_e$  is under normal growth conditions, calculate the grain distribution of photosynthetic product coefficient of 1 day before;  $a_{sl}$ ,  $b_{sl}$ ,  $a_{se}$ ,  $b_{se}$ ,  $c_{se}$ ,  $a_m$ ,  $b_m$  and  $RDS_g$  are undetermined coefficient.

Based on the test of root, stem, leaf and grain dry matter weight to calculate  $K_{sl}$ ,  $K_{se}$  and  $A$  doing regression analysis by corresponding  $RDS$ . Obtain the outstanding parameter in table 5.



**Table.5.** The parameters of stem leaves, grain stem and root shoot growth equilibrium model

| Name            | Parameter name  |                 | Correlation coefficient R <sup>2</sup> |
|-----------------|-----------------|-----------------|--|
| K <sub>sl</sub> | a <sub>sl</sub> | b <sub>sl</sub> | 0.9601                                 |
|                 | 4.5472          | 2.233           |  |
| K <sub>se</sub> | a <sub>se</sub> | b <sub>se</sub> | RDS <sub>g</sub><br>0.72<br>0.9806     |
|                 | 20.2147         | -26.85          |  |
| A               | a <sub>m</sub>  | b <sub>m</sub>  | 0.9484                                 |
|                 | 0.3379          | -1.2931         |  |

### 3.2.3 Index of Water Nutrient Stress and Calibration of Photosynthetic Conversion Efficiency and Inspection of Crop Water Model.

Photosynthetic conversion efficiency and index of water stress and index of nutrient stress. Fitting by the root, stem, leaf and kernel dry matter weight. Using data of the 2008 and 2009 with high water and fertilizer treatment (treatment 1), zero water and zero fertilizer treatment (treatment 5). Fitting result is  $Yg=0.66$ ,  $\sigma=0.80$ ,  $\lambda=1.0$ . Correlation coefficient R<sup>2</sup> of root, leaf, stem and grain are 0.902, 0.771, 0.846 and 0.951. Average relative error is 21.4%, 29.6%, 22.8% and 21.2%. Sample number is 17. The results of the simulation were the best. The correlation coefficient between the simulated value and the measured value is the maximum. Relative error is also small. With the increasingly dry matter weight, there was a significant download trend in the relative error of the simulated values of dry matter in each treatment. To the harvest, the mean value of relative error is reduced to 10.7%.

Using 2008 and 2009 processing 2 ~ 4, a total of six processing dates, to testing the overall rationality of the model. Thus, correlation coefficient of root, leaf, stem and kernel is 0.7966, 0.7041, 0.9717 and 0.9858. The average relative error is 38.7%, 28.3%, 13.6% and 16.6%, sample number is 51. Correlation coefficient of stems and grains is bigger and relative error is little, especially the best result of forecasting output and correlation coefficient to more than 0.98, indicating the constructed model and its parameters can be used well in predicting effects of quantity and time of irrigation and fertilization on crop yield. Moreover, the simulation accuracy of weight of stem and grain weight is better than setting accuracy of the parameter rate, the main reason is parameters rate timing using the maximum and minimum irrigation and fertilization treatment, the obtained parameters can cover a wide range.

In the same time, with the increasing of dry matter weight, relative error of the simulated the values of grain dry weight under different treat men are also decreases obviously, in harvest time, average relative error of grain dry weight was reduced to 3.7%, means the simulation precision of crop yield is higher.

### 3.4 Parameter Values and Results of Optimization Model of Irrigation System

Table 6 is the results of optimization model parameters of irrigation system. The price includes irrigation labor and other expenses, where C is other agricultural inputs except irrigation water do not change with the irrigation water. The overwinter water not only increased soil moisture effect, but also have the effect of water storage and root growth. This study has no optimization calculation, just give the winter water according to the experience of the irrigation time.

**Table.6.** The model parameters of optimizing irrigation scheduling for winter wheat

| Parameter name | $t_1/d$ | $t_2/d$ | $t_m/d$ | $m/mm$ | $\eta$ | Water price<br>$P_w/RMB/m^3$ | Product price<br>$P_c/RMB/kg$ | Agricultural input<br>$C_0/RMB/hm^2$ |
|----------------|---------|---------|---------|--------|--------|------------------------------|-------------------------------|--------------------------------------|
| Value          | 60      | 10      | 253     | 60     | 0.5    | 0.3                          | 2.5                           | 3150                                 |

Frequency analysis made based on the series of meteorological data from 1951 to 2013 in Tianjin city and growing season precipitation. The five typical years are given in corresponding frequencies of 5%, 25%, 50%, 75% and 95%. The basic situation of each typical year and the output and benefit of irrigation times of maximum irrigation benefit in table 7. From table 7 with the increasing of drought degree and irrigation times, depending on 3 times in the 5% typical year to 6 times in 95% typical year. It is shown that when the irrigation water supply is little, average temperature is low, potential evapotranspiration is little only 458.2mm close to the 5% typical year. Therefore, the irrigation times are the same as the 5% typical year. In five typical years, 95% typical year the output and benefit were the largest. The main reason is the large number of sunshine hours, the average temperature is high, to provide sufficient heat resources for crop growth.

Figure 1 and figure 2 shows the relationship between output and benefit under different irrigation water supply conditions. The figure shows that when irrigation water supply is small greatly variation amplitude of increasing yield, when the amount of irrigation water is more than 3 times. No matter the typical year, mutative amplitude of increasing yields is reduce; the corresponding irrigation production efficiency is obviously tending to be flat or decreasing. Thus, 3 times of winter wheat growing period irrigation is reasonable economic. The results are very consistent with the local production of the actual situation.

**Table.7.** The weather situation during winter wheat growing period in typical year

| Project                               | Frequency of different typical years of Winter Wheat |           |           |           |           |
|---------------------------------------|--|-----------|-----------|-----------|-----------|
|                                       | 95%  | 75%       | 50%       | 25%       | 5%        |
| $ET_m/mm$                             | 579.55   | 458.2     | 578.99    | 560.45    | 441.92    |
| precipitation/mm<br>water quantity    | 63.4   | 95.6      | 119.3     | 165.7     | 226.2     |
| Mean<br>temperature / $^{\circ}C$     | 7.2  | 6.9       | 6.8       | 7.5       | 7.8       |
| Accumulative<br>total sunshine time/h | 1908   | 1519      | 1909      | 1791      | 1510      |
| The actual date                       | 1959-1960  | 1984-1985 | 1970-1971 | 1972-1973 | 1997-1998 |

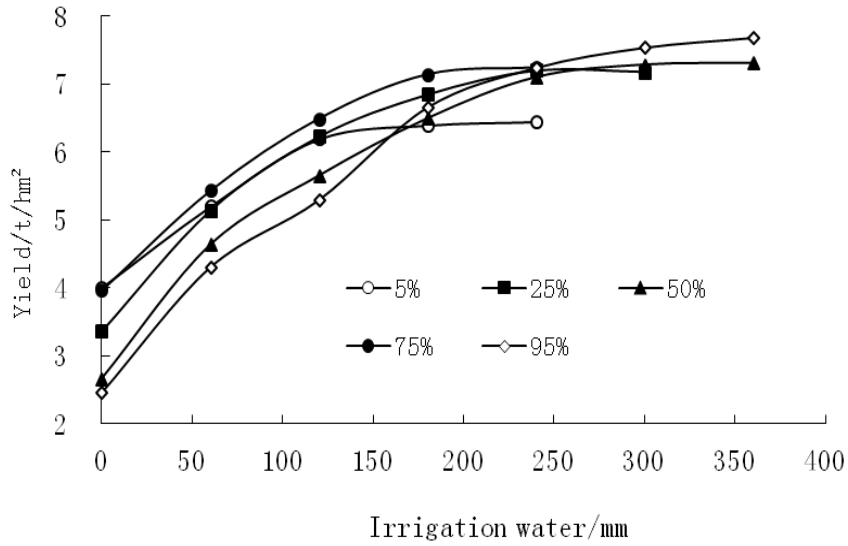


Fig.1. The relationship between winter wheat yield and irrigation water supply

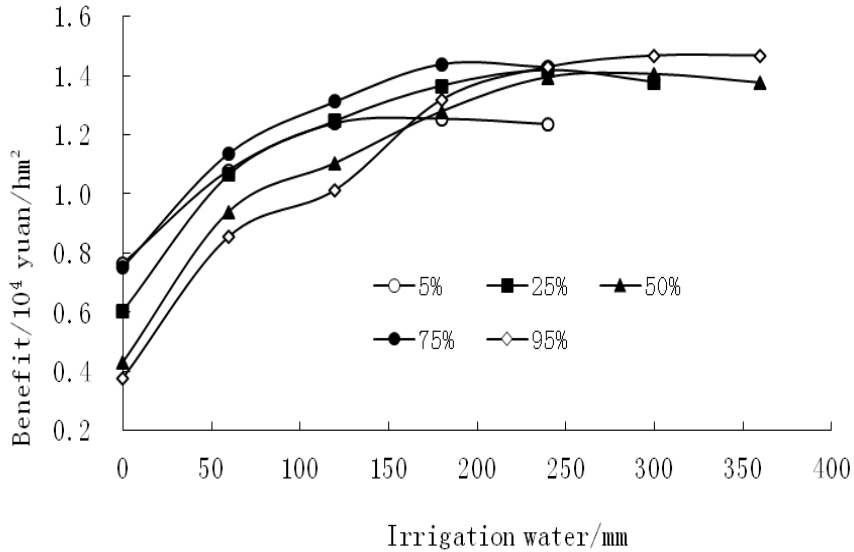


Fig.2. The relationship between winter wheat benefit and irrigation water supply

### 3.5 The Analysis Result of Winter Wheat under Dynamic Irrigation Low Limit Value

The optimization of the irrigation schedule on the basis of the five typical years, every typical year from irrigation one time until to get maximize benefit irrigation, 58 group of soil moisture content can be obtained (average from 0 to 60 cm ) and the corresponding irrigation time and water supply. Compared formula (7) calculation of irrigation low limit value with the measured values (optimized irrigation schedule data obtained from different typical years), the objective function is minimum error variance. The multiple regression analysis are deduced with the method of Excel software in the planning tools to solve the alternate, obtained the undetermined index in type (7) and the undetermined coefficients (table 8).

Table.8. The parameters of model for forecasting winter wheat irrigation low limit

| Parameter name | The parameters of model for forecasting Winter wheat irrigation low limit                 |       |       |       |         |       |        |         |
|----------------|---|-------|-------|-------|---------|-------|--------|---------|
|                | $m$   | $n$   | $p$   | $q$   | $a_0$   | $a_1$ | $a_2$  | $a_3$   |
| Value          | 8.659   | 0.528 | 1.001 | 0.682 | -0.0539 | 0.235 | 0.0309 | -0.0015 |
| Note           | Correlation coefficient $R = 0.6541$ , $F = 8.23$ , Significant level $\alpha = 0.000317$ |       |       |       |         |       |        |         |

By table 8, the correlation coefficient reaches 0.65 above between dynamic irrigation low limit value and irrigation time and supply amount, significant index  $\alpha=0.000317$ , far less than 0.01, reached extremely significant level. Showed that type (7) could be used to forecast the dynamic irrigation low limit value of winter wheat growth period and its applicable range to 1 times irrigation to achieve maximum irrigation benefit when irrigation frequency.

### 3.6 Winter Wheat Dynamic Low Limit Value in the Application of Irrigation Forecast

#### 3.6.1 Irrigation Forecasting Process and Increase Production Efficiency Analysis

To monitor soil moisture content for the initial moisture content, use soil moisture dynamic simulation model for predicts soil moisture content on a daily (0-200cm). When the prediction soil moisture content (average from 0 to 60 cm) less than or close to the irrigation low limit value, forecast the irrigation, otherwise no forecast. In the process, using the adjacent ten days on the relationship between the amount of reference crop evapotranspiration and the relationship between the adjacent two ten days temperature forecasting crop water requirement and the temperature, precipitation forecasted by nearly 10 years of daily mean, irrigation low limit value use type (7) to calculate.

In order to reduce the influence of the meteorological factors such as precipitation change, for nearly five years (2009~2013) supply amount 3 times irrigation and 2 times irrigation, has carried on the winter wheat irrigation time forecast year by year, irrigation quota adopt 60 mm. As a preliminary study, the use of crop water model gives the corresponding production and efficiency (table 9). At the same time, use the meteorological data from 1998 to 2007 to optimization calculation can obtained the optimized irrigation time, on the basis of calculation, recent five years (table 9) of winter wheat yield and benefit is given, as experience irrigation (not do irrigation forecast) to yield and benefit.

**Table.9.** The difference between the winter wheat benefit and production yield under forecasting and experience irrigation

| Year    | Irrigation forecast/3 times irrigation |                         |                            | Experience irrigation/3 times irrigation |                         |                            | Yield increase/% | Synergism/% |
|---------|--|-------------------------|----------------------------|--|-------------------------|----------------------------|------------------|-------------|
|         | Irrigation time/d                      | yield/t/hm <sup>2</sup> | profit/RMB/hm <sup>2</sup> | Irrigation time/d                        | yield/t/hm <sup>2</sup> | profit/RMB/hm <sup>2</sup> |                  |             |
| 2009    | 75/190/219                             | 7.227                   | 14625.9                    | 70/185/216                               | 7.050                   | 14183.0                    | 2.51             | 3.12        |
| 2010    | 75/190/215                             | 5.827                   | 11125.6                    | 70/185/216                               | 5.496                   | 10299.0                    | 6.02             | 8.03        |
| 2011    | 75/180/200                             | 6.814                   | 13591.7                    | 70/185/216                               | 6.171                   | 11985.0                    | 10.42            | 13.41       |
| 2012    | 75/190/220                             | 6.463                   | 12715.4                    | 70/185/216                               | 6.099                   | 11804.0                    | 5.97             | 7.72        |
| 2013    | 75/190/210                             | 5.630                   | 10632.4                    | 70/185/216                               | 5.365                   | 9970.0                     | 4.94             | 6.64        |
| average |  | 6.484                   | 12538.2                    |  | 6.036                   | 11648.2                    | 7.42             | 7.64        |
| Year    | Irrigation forecast/2 times irrigation |                         |                            | Experience irrigation/2 times irrigation |                         |                            | Yield increase/% | Synergism/% |
|         | Irrigation time/d                      | yield/t/hm <sup>2</sup> | profit/RMB/hm <sup>2</sup> | Irrigation time/d                        | yield/t/hm <sup>2</sup> | profit/RMB/hm <sup>2</sup> |                  |             |
| 2009    | 75/194                                 | 6.256                   | 12558.4                    | 70/204                                   | 5.560                   | 10817.0                    | 12.52            | 16.10       |
| 2010    | 75/195                                 | 5.074                   | 9602.1                     | 70/204                                   | 5.165                   | 9830.0                     | -1.76            | -2.32       |
| 2011    | 75/188                                 | 6.397                   | 12909.4                    | 70/204                                   | 5.970                   | 11842.0                    | 7.15             | 9.01        |
| 2012    | 75/191                                 | 5.724                   | 11228.1                    | 70/204                                   | 5.079                   | 9614.0                     | 12.70            | 16.79       |
| 2013    | 75/194                                 | 4.557                   | 8310.2                     | 70/204                                   | 4.674                   | 8602.0                     | -2.50            | -3.39       |
| average |  | 5.602                   | 10921.6                    |  | 5.290                   | 10141.0                    | 5.62             | 7.24        |

Note: 1. the irrigation time expressed in the number of days have elapsed since the date of seeding, d;  
2. all of irrigation water quota are 60 mm.

It can be seen from table 9, due to the randomness change of the meteorological factors, the calculation of the benefit of five annual outputs and benefit both big and small, even production. However, the overall situation is under the condition of limited water supply irrigation forecast has obvious increase production efficiency, 3 times irrigation and 2

times irrigation five-year average increase the yield of 7.42% and 5.62% respectively, the increase efficiency of 7.64% and 7.24%, respectively.

As a preliminary study, analysis of irrigation forecast, nearly 10 years of daily mean precipitation was adopted, crop water requirement and the temperature forecast adopted nearly 10 days of real-time data, if reuse weather forecast information, more prediction increment and increase production efficiency.

## 4 Conclusion

The relationship between dynamic irrigation low limit value and irrigation time and the water supply reached a significant level, the irrigation low limit value can be used predict the dynamic low limit water in winter wheat growing period , and applies to the whole range from 1 times irrigation to economic irrigation.

Soil moisture and soil nitrogen dynamic simulation model, the crop growth model, and the parameters model by analysis to determine are reasonable and reliable, and can be used for the simulation calculation of the impact of irrigation festination to crop yield. Furthermore, this model can effectively describe heat resource such as sunshine, temperature change on the influence of crop growth and yield.

Under the condition of Limited water supply using dynamic water low limit value for irrigation forecast has obvious increase production efficiency, if make full use of the weather forecast information, even bigger prediction increment and increase production efficiency.

This study put forward theoretical analysis method of dynamic water low limit, changed the way only rely on field trials to determine the practice of irrigation low limit. To a certain extent, enrich and perfect the theory of farmland irrigation, provide an important method to optimal irrigation schedule implementation and dynamic correction of irrigation area under the condition of limited water supply.

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