Study on the Dynamic Low Limit of Irrigation for Winter Wheat

Hongzheng Shen, Yangren Wang

Study on the Dynamic Low Limit of Irrigation for Winter Wheat

Hongzheng Shen[1], Yangren Wang [1(✉)]

[1]Tianjin Agricultural University, Tianjin 300384, China
18920098683@163.com, OCRD:0000-0002-8698-2863; wyrf@163.com.

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^3 and water of shortage per unit area is 1400 and 910 m^3/ hm^2, 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

$$P_{di} = P_{dmi} \cdot FW_i \cdot FN_i \tag{1}$$

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

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

$$P_{dmi} = F_{gci} \cdot Y_g \; 30/4 \tag{2}$$

Where F_{gci} is the daily obturation reference to crop's total carbon dioxide absorption rate, kg/ hm^2/d is calculated by the formula given by P.M. Driessen. 30/44 is the ratio of the molecular weight of CH_2O and CO_2; 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]:

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

$$FN_i = \left(R_{tpyN}(t) \right)^{\lambda} \qquad 0 < FN_i \le 1 \tag{4}$$

$$R_{tpyN}(t) = \min[1, P_N(t) / P_{crtN}(t)] \tag{5}$$

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. σ is the water stress index, reflects the degree of sensitivity of the impact water deficit on crop growth. λ 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. $P_{crtN}(t)$ 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

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

Constraint condition, mainly by irrigation time limit

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

Where B is the net-income of per unit area, RMB/hm^2; y is the crop yield, kg/hm^2. 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; η 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^3), considering the irrigation labor cost in the irrigation water price. C_0 is the irrigation water of other agricultural inputs, RMB/hm^2, 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.

$$\theta_l = a_0 + a_1 t_r^m + a_2 W^n + a_3 W^p t_r^q \tag{8}$$

Where θ_l is the dynamic irrigation low limit value, expressed by average soil moisture content at the soil depth of 0-60cm, cm^3/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°57′, north latitude 39°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 $1hm^2$. 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 $80m^3$ 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	θ_s/ cm^3/cm^3	θ_r/ cm^3/cm^3	α	n	K_s/ cm/d	Soil bulk density /g/cm^3	Field Capacity/cm^3/cm^3
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

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

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

Where θ is the soil moisture content,cm^3/cm^3; θ_s is the saturated water capacity,cm^3/cm^3; θ_r is the soil residual water content,cm^3/cm^3; 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; $m=1-1/n$; α 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

Transaction Number	process context	Quantity of base fertilizer/kg/hm^2	Quantity of additional fertilizer /kg/hm^2	Irrigation amount /m^3/hm^2	irrigation requirement/m^3/hm^2				gauging pipe number
					Hibernate	Jointing	earing	grouting	
1	H180	750	225	1800	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^2. The quantities of drilling are 225, 150 and 0 kg/hm^2.

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^{-1} mineralization	Nitrification rate Kn/min^{-1}	evaporation rate Kv/min^{-1}	Root nitrogen absorption

Name	μ/cm	τ_α	rate				coefficient Kr
parameter values	5	0.5	0.17	1.3×10^{-8}	3.64×10^{-5}	1.48×10^{-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:

$$K_{\mathrm{sl}} = a_{sl} \cdot RDS^{b_{sl}} \tag{11}$$

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

$$A = R_m(\beta_e \cdot f_e + \beta_s \cdot (1 - f_e)) \tag{13}$$

Where

$$R_m = a_m RDS^{b_m} \tag{14}$$

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

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

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 ,℃;T_0 is the whole growth period of effective accumulated temperature of winter wheat ℃; R_m is the root shoot ratio under normal growth conditions of winter wheat; β_e and β_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^2
K_{sl}	a_{sl} 4.5472	b_{sl} 2.233		0.9601
K_{se}	a_{se} 20.2147	b_{se} -26.85	RDS_g 0.72	0.9806
A	a_m 0.3379	b_m -1.2931		0.9484

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^2 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	η	Water price $Pw/RMB/m^3$	Product price Pc/RMB/kg	Agricultural input $C_0/RMB/hm^2$
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 458.2m 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 water quantity	63.4	95.6	119.3	165.7	226.2
Mean temperature /℃	7.2	6.9	6.8	7.5	7.8
Accumulative total sunshine time/h	1908	1519	1909	1791	1510
The actual date	1959-1960	1984-1985	1970-1971	1972-1973	1997-1998

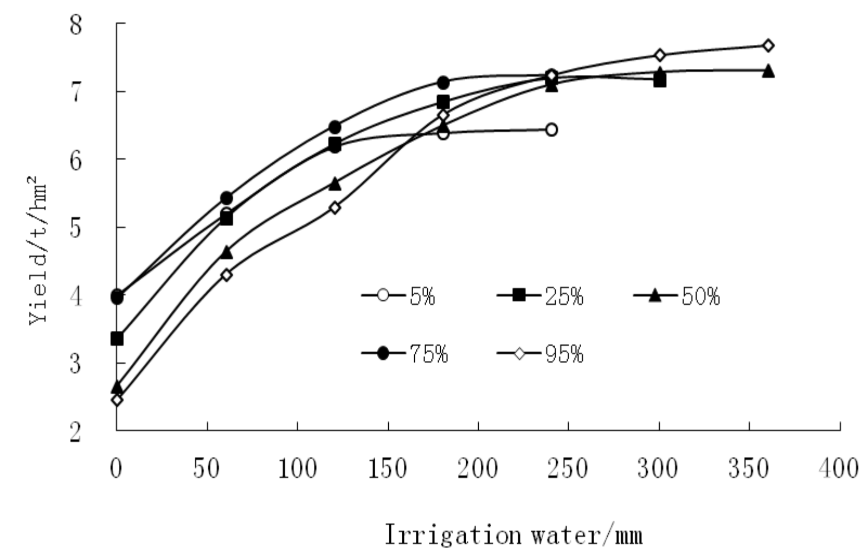

Fig.1. The relationship between winter wheat yield and irrigation water supply

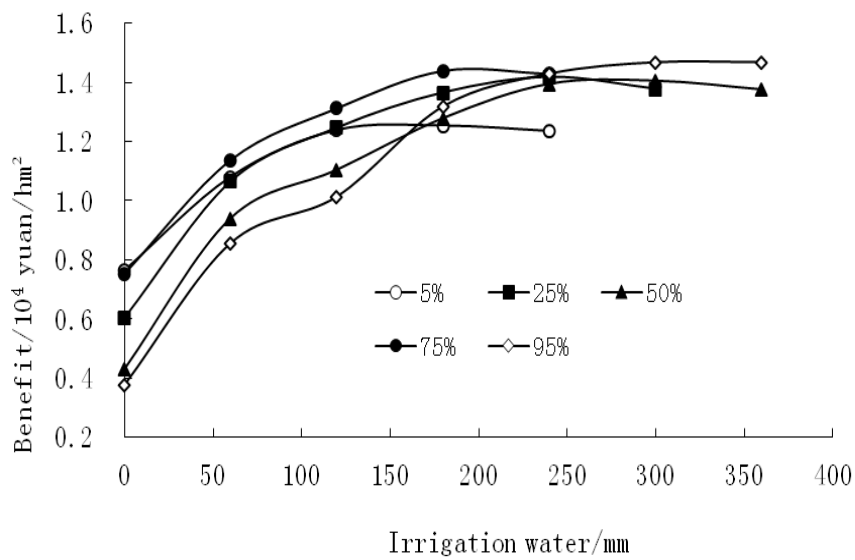

Fig.2. The relationship between winter wheat benefit and irrigation water supply

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 α＝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 α=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^2	profit/RMB /hm^2	Irrigation time/d	yield /t/hm^2	profit/RMB// hm^2		
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
	Irrigation forecast/2 times irrigation			Experience irrigation/2 times irrigation				
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.

Acknowledgment

The National Science and technology support program No.2012BAD08B01 supported this work. Study on the patterns of festination dynamic decision-making and implementation. The foundation of application and research is in cutting-edge technologies project in Tianjin. No.10JCYBJC09400, 2010.1-2013.3.

Reference

1. Qian, Z.Y., Zhang, G.D.: Comprehensive report and various thematic reports of China's water resources sustainable development strategy research [M]. Beijing, Journal of China Water Resources and Hydropower Engineering. 202-251(2001)
2. Kang, S.Z., Du, T.S., Sun, J.S., Ding, R.S.: Theory and technology of improving irrigation water use efficiency based on crop growing water demand information [J]. Journal of hydraulic Engineering. 38(6), 90-95 (2001 in Chinese)
3. Zhang, X.Y., Pei, D., You, M. Z.: Field studies on optimum irrigation scheduling for winter wheat in the piedmont of Mt.Taihang[J]. Journal of hydraulic Engineering. 32(1), 90-95(2001 in Chinese)
4. Wang, Y.R., Sun, X.P.: Theory of Shanxi agricultural water saving and model of efficient water using [M]. Press of Science and Technology of China. (2003)
5. Wang, J.D., Gong, S.H., Du, L.L., Xue, J.B., Zi, Y.: The developing status and future study emphases on limited irrigation [J].Journal of Irrigation and Drainage. 30(6), 6-10(2011 in Chinese)
6. Rong, F.T.: A preliminary study of the water-saving irrigation scheduling [J].Water Resources and Hydropower Engineering. (7), 8-13(1986 in Chinese)
7. Liu, Z.J., Li, B.P., Li, Y.H., Cui, Y.L.: Research on the water use efficiency and optimal irrigation schedule of the winter wheat [J]. Transactions of the CSAE. 20(4), 58-63(2004 in Chinese)
8. Shang, S.H.: Simulation of optimization method for crop irrigation scheduling with limited water supplies [J]. Journal of Tsinghua University: Science and Technology. 45(9), 1179-1183(2005 in Chinese)

9. Qie, Z.H., Han, L.M., Wu, X.M.: Optimization of Crop Irrigation Quantity and Irrigation Date Based on the Improved NSGA-II[J]. Transactions of the Chinese Society for Agricultural Machinery. 42(5), 106-110(2011 in Chinese)
10. Singh, A.K., Tripathy, R., Chopr, U.K.: Evaluation of CERES-Wheat and CropSyst models for water–nitrogen interactions in wheat crop [J]. Agricultural water management. 95,776-786(2008)
11. Behera, S.K., Panda, R.K.: Integrated management of irrigation water and fertilizers for wheat crop using field experiments and simulation modeling [J]. Agricultural Water Management. 96(11), 1532-1540(2009)
12. Cui, Y.L., Yuan, H.Y., Li, Y.H.: The optimum irrigation scheduling for rice with stochastic rainfall under limited water supply [J]. Journal of hydraulic Engineering. 30(7), 40-46(1999 in Chinese)
13. Wang, S.F., Duan, A.W., Zhang, Z.Y., Xu, J.X.: Winter wheat irrigation schedule on stochastic precipitation [J]. Transactions of the CSAE. 26(12), 47-52(2010 in Chinese)
14. Ganji, A., Ponnambalam, K., Khalili, D.: A new stochastic optimization model for deficit irrigation [J]. Irrigation Sci. 25, 63-73(2006)
15. Villalobos F.J., Fereres, E.: A simulation model for irrigation scheduling under variable rainfall [J]. American Society of Agricultural Engineers. 32 (1), 181-188(1989)
16. Shen, X.J., Sun, J.S., Liu, Z.G., Zhang, J.P., Liu, X.F.: Effects of low irrigation limits on yield and grain quality of winter wheat [J]. Transactions of the CSAE. 26(12), 58-65.(2010 in Chinese)
17. Sun, J.S., Liu, Z.G., Xiao, J.H.， etc.: Research on water-saving irrigation upper and lower limit for winter wheat [J]. China Rural Water and Hydropower. (9), 10-12(1998 in Chinese)
18. Sriramany, S., Murty, V.: A real-time water allocation model for large irrigation systems [J]. Irrigation and Drainage Systems. 10(3), 109-129(1996)
19. Mao, Z., Li, Y.H., Li, H.C.: Real-time forecast of irrigation [J]. Engineering Science. 4(5), 24-33(2002 in Chinese)
20. Ma, J.Q., Liu, L., Zhang, Z.W., Hao, X.P., Peng, G.H.: theory of real-time irrigation water use in agriculture and integrated management system [M]. Beijing journal of China Water Resources and Hydropower Engineering. 29-53(2013)
21. Rogers, D.H., Elliot, R.L.: Irrigation scheduling using crop growth simulation risk analysis and weather forecasts [J]. Transcation of ASAE. 32, 1669-1677(1989)
22. Hou, J.W., Luo, Y.F., Cui, Y.L.: Analysis of rainfall forecast accuracy and its application in water-saving irrigation decision-making for rice [J]. Water-Saving Irrigation. (3):24-30(2013 in Chinese)
23. Ma, J.Q., Wang, W.Z.: Soil moisture on-line forecasting and real-time irrigation schedule model for winter wheat [J].Water Resources and Power.31(10),139-141,188(2013 in Chinese)
24. Yang, L.X., Wang, Y.R., Guo, X., etc.: Research on irrigation forecast not under the condition of irrigation forecast under an insufficient water supply[z]. China Science and Technology Achievements.1-8(2012 in Chinese)
25. Bai, W., Feng, S.Y., Kang, S.Z.: Optimization of deficit irrigation schedule based on web[J].Transactions of the CSAE. 22(12), 56-59(2006 in Chinese)
26. Brown, P.D., Cochrane, T.A., Krom, T.D.: Optimal on-farm irrigation scheduling with a seasonal water limit using simulated annealing [J].Agricultural Water Management. 97(6), 892-900(2010)
27. Holland, P.M., Driessen, N.T., Konijn, W., Yu, Z.R., Wang, J.W., Qiu, J.J., etc.: the analysis on land use system [M]. Beijing: China Agriculture Science and Technique Press. 105-164 (1997 in Chinese)
28. Shi, J.Z., Wang, T.D.: The mechanism model of photosynthate distribution during the vegetative growth [J]. Acta Botanica Sinica. 36(3), 181-189(1994 in Chinese)
29. Wang, Y.R.: Research on SPAC dynamic hydrothermal and crop Growth simulation by considering water and nutrition stress [D]. Northwest A&F University(2004)
30. Lei, Z.D., Yang, S.X., Xie, S.C.: Soil hydrodynamics [M]. Beijing, Tsinghua University press. 57-78(1988)
31. Kang, S.Z., Liu, X.M., Xiong, Y.Z.: the theory and application of the soil plant atmosphere continuum (SPAC). [M] Beijing Water Conservancy and Electric Power Press. 85-121(1994)
32. Shang, S.H., Mao, X.M., Lei, Z.D., etc.: soil moisture dynamic simulation model and application [M]. Beijing Science press. 63-85, 101-148(2009)
33. Ritchie, J.T. Soil water balance and plant water stress. Gordon Y.T., Hoogenboom, G., Philip, K.T.: Understanding Options for Agricultural Production [M]. Kluwer Academic Publishers, Printed in Great Britain. 41-54(1998)

34. Wang, K.: unsaturated soils water flow and solute transport [M]. Beijing: journal of scientific. 97-103(2010)
35. Wang, X.P., Huang, G.H., Yu, L.P., Huang, Q.Z.: Coupled simulation on soil-water-nitrogen transport and transformation and crop growth [J]. Transactions of the CSAE. 27(3), 19-25(2011 in Chinese)
36. Shao, D.G., Guo, L.G., Wang, X.G., Hong, Lin., etc.: efficient use of water and fertilizer resources [M]. Beijing: journal of scientific. 139-151,(2012)
37. Van, G.M.: A closed-form equation for predicting the Hydraulic conductivity of unsaturated soils [J]. Soil Sci. 44(5), 892-898(1980)
38. Li, J.S., Zhang, J.J., Xue, K.Z.: Drip irrigation fertigation principle and application [M]. Beijing, China Agriculture Science and Technique Press. 128-155(2003)
39. Xu, D., Liu, J., Yang, D.W., Zhang, B.Z., etc.: evapotranspiration expand of effect sizes and temporalspatial scales [M]. Beijing, journal of scientific. 313-359(2015)
40. Ren, L., Mao, M.: pesticide imitate in soil transport [M]. Beijing: journal of scientific. 50-58(2008)
41. Duan, A.W., Sun, J.S., Liu, J., etc.: Main crops irrigation quota in northern regions [M]. Beijing: China Agriculture Science and Technique Press. 210-242(2004)