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Adaptive irrigation scheduling for winter wheat under drought conditions in North China

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ABSTRACT

In order to relieve the water shortage for irrigation in North China, an adaptive real-time irrigation scheduling based on weather forecast and drought evaluation was developed. First, drought degree was evaluated into five ranks in crop growing seasons, and then the irrigation threshold was decided based on the chosen drought evaluation indexes, finally using field water balance principle and soil moisture simulation technology, an adaptive real-time irrigation scheduling was established to adapt to climate changes and actual rainfall based on winter wheat filed experiments from 2011 to 2014 in this study. Results showed that the irrigation water depths in 2013–2014 provided by the traditional irrigation schedule was 266 mm, which was much higher than that provided by adaptive real-time irrigation schedule (177 mm). Though the yield and water productivity provided by adaptive real-time irrigation were not the highest among different irrigation treatments, it is more suitable for the application adaptive real-time irrigation in North China to cope with the limited water resources of the irrigation districts.

Keywords: Irrigation scheduling; Soil moisture; Winter wheat; Drought evaluation; North China

1. Introduction

Drought is a major constraint for agriculture [1–3]. Irrigation is essential for crops especially in arid area to mitigate potential yield reductions and meet food safety [4,5]. Under the impact of climate change, rapid economic development, and the intensification of agricultural and industrial water disputes, the available irrigation water become less and less, water shortage in agriculture has posed a great threat to food security in North China [6,7]. Hence, it is important to make reasonable irrigation schedule to improve water use efficiency and crop yields production, including irrigation water amount and irrigation times.

Insufficient irrigation can enhance water use efficiency and maximize crop water productivity, instead of maximizing the harvest food product per unit land by controlling water at crop growing stage and largely maintain total crop yield [3,8,9]. Due to the severe water shortage in North China, a series of studies about the insufficient irrigation scheduling have been carried out [10,11].

Irrigation threshold is vital for insufficient irrigation [12,13]. Most of the traditional insufficient irrigation threshold was determined empirically based on given values of experience. Developing the thresholds considering environmental condition changes is an important work in limited irrigation [13,14]. The determination of irrigation thresholds should take into account both the dynamic drought changes and the influence of insufficient water supply under arid condition and limited water constrains. But just few researches about irrigation threshold considering both the dynamic drought and water shortage have been carried out [15]. A new irrigation schedule methodology,

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which gives the irrigation threshold based on the dynamic drought and water shortage, should be developed.

Another important factor for irrigation scheduling during soil water balance calculation is the estimation of evaporation and rainfall. In earlier studies, irrigation schedule was designed based on typical water year, which means to use the rainfall of chosen typical water year to calculate the optimal irrigation water allocation [16–18]. This kind of irrigation schedule did not really work well in practice due to the obvious difference in spatial and temporal distribution of precipitation between typical water year and the real coming year [16].

Hence, it is important to make best use of the available precipitation so as to relieve water shortage. Due to the randomness of rainfall and its important impact on irrigation systems, the monitoring and forecasting methods of rainfall and closely related soil moisture content have been extensively studied and developed rapidly. Instruments such as neutron probe, remote sensing and spatial information technology have been used to measure the changing rainfall and soil moisture content data. At the same time, irrigation forecast models for the soil moisture dynamics prediction or irrigation water requirements prediction in the field were proposed and improved [19–23].

Research on irrigation schedule started in 1980s in China. Models such as soil water prediction model, real-time irrigation process and other improved prediction methods were proposed, and monitoring measurement were also used in the research field [24,25].

The development of internet made it became true that irrigation schedule could be ‘real time’ and ‘accurate’. Real-time irrigation schedule based on ‘real-time’ monitoring data and short-term weather forecast data is the main foundation of dynamic water allocation. Therefore, compared with the previous irrigation schedules, the obvious advantage of real-time irrigation is to maximize the use of rainfall, effectively improve the water use efficiency especially in drought area [26–28].

Under the impact of drought, crops yield reduction occurs frequently in North China. It often requires a lot of irrigation to guarantee crop growth during the crop growing season due to the inconsistency between rainfall and crop water demand. However, the effective utilization of rainfall is very low by means of traditional irrigation in North China. The objective of this paper is to provide an adaptive methodology for real-time irrigation scheduling based on field experiment, which can be applied to limited irrigation system, taking both the dynamic drought environment and real-time rainfall into account to solve the efficient use of rainfall and the appropriate irrigation threshold problem.

2. Materials and methods

2.1. Study area

Field experiments were conducted at Agricultural experiment field of North China University of Water Resources and Electric Power (NCWU), located in Zhengzhou (34°16′–34°58′N, 112°42′–114°14′E), Henan province, which lies in the North China.

The mean annual rainfall is about 640.9 mm, ranging from 380 to 1,041 mm (1956–2016), and about 70% of the rainfall falls from June to September. The annual mean temperature is 14.4°C, the maximum monthly temperature is 27.3°C, occurring in July, and the minimum is 0.2°C, occurring in January. The frost free period is 220 d; the annual sunshine hours reach 2,400 h. This area is suitable for winter wheat which is one of the main crops in North China.

The soil texture is sandy loam with field capacity (FC) of 0.42 ($m^3\ m^{-3}$). Soil porosity is 0.4 and soil dry bulk density is 1.44 g cm^{-3}.

2.2. Field experiments and data collections

Winter wheat experiments were carried out on a region with an area of 500 m^2, which were divided into four rows, each with two replicates named A(A_1, A_2), B(B_1, B_2), C(C_1, C_2), and D(D_1, D_2) (Fig. 1, Table 1). Area of each individual plot was 12.0 m × 5.0 m. Plots were isolated from each other by means of soil bunds.

Winter wheat experiments were carried out from 2011 to 2014. Rainfall during the winter wheat growth season usually does not meet the crop’s water requirements in North China. Therefore, to reflect the water consumption of winter wheat under different water supply levels, the four treatments were set as four different water supply levels: 80%–100% FC (A_1, A_2), 60%–90% FC (B_1, B_2), 50%–90% FC (C_1, C_2), adaptive irrigation (D_1, D_2). For example, 80%–100% FC treatment means when the soil water storage in the top 60 cm soil layer was less than 60% FC, irrigation was applied to fill the 60 cm soil layer to 100% FC. Adaptive irrigation means different irrigation threshold changing with drought degree, which is described in the section of “drought degree and its corresponding adaptive irrigation threshold”.

Soil water content (SWC) was measured once daily with EnviroSCAN (ES) system (Sentek Pty Ltd., Australia). In the middle of each plot, an ES system with a frequency domain reflectometry was installed by inserting 200 cm into the soil, allowing for the measurement of volumetric SWC during the growing season (Fig. 1). The daily soil moisture at different depths were measured using 20 non-interfering sensors, which were buried at a spacing of 10 cm. SWC was determined by integrating data gained with the ES system within the depth of the root zone.

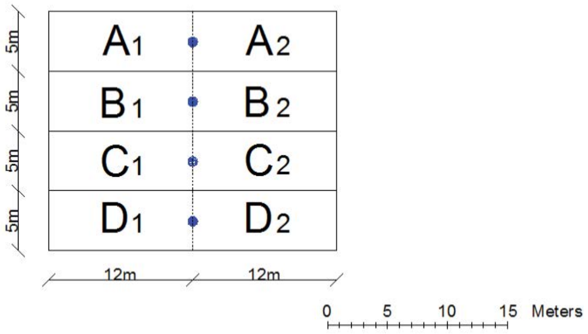

Fig. 1. Layout of winter wheat experimental plots (Dots indicate the position of EnviroSCAN system in the plot).

Table 1
Winter wheat plot treatment and water supply level

Treatment	Upper threshold	Lower threshold	Sowing type
A	FC	80% FC	Normal sowing
B	90% FC	60% FC	
C	90% FC	50% FC	
D	Changing with drought degree		

Note: FC, field capacity.

According to the measured SWS, each plot was irrigated based on its assigned irrigation treatment. A sprinkler and micro-irrigation system was used in growing season.

Winter wheat was sowed on 10 October and harvested in next early June. Samples of final biomass and grain yield were collected at maturity from an area of 2 m × 2 m in each plot.

The weather data are measured by small automatic weather station (SAWS) in the field. The weather forecast data are obtained from State Meteorological Agency, http://www.weather.com.cn/forecast/.

2.3. Crops' adaptive real-time irrigation schedule based on drought circumstances

Aridity poses a major constraint on land productivity and the consequence of food production [1]. Therefore, it is important to estimate the degree of drought in the crop season and determine the irrigation threshold from the degree of drought.

2.3.1. Drought evaluation indexes in crop growth season

2.3.1.1. Drought evaluation indexes

Drought evaluation indexes (DEI) are a quantitative expression of drought. There are nearly 60 species of DEI and can be divided into four categories, namely meteorological drought index, hydrological drought index, agricultural drought index and socio-economic drought index. However, due to the differences in hydrological, meteorological and agricultural conditions, the same DEI is different in different regions of the drought classification criteria. Although many researches had been carried out on DEI, there is no universally accepted DEI due to the complexity influencing factors on droughts [29,30]. So in order to assess regional drought, a DEI system should be established to compensate the insufficient evaluation of single DEI [29,31].

In this study, percentage of precipitation anomaly (PPA), continuous rainless days (CRD) of meteorological drought index and soil relative moisture (SRM) of agricultural drought index were selected to establish the evaluation index system. According to the "Classification of Meteorological Drought Category" [32] and "Standard of Classification for drought severity" [33], drought degree is divided into no drought (ND), light drought (LD), medium drought (MD), severe drought (SD) and extreme drought (ED) degree.

PPA and SRM can be obtained by these following formulae [32,34,35]:

$$\mathrm{PPA}_i = \frac{p_i - \bar{p}_i}{\bar{p}_i} \tag{1}$$

where p_i is the precipitation during period i (mm), $\bar{p}_i$ is the mean precipitation during the same period i (mm).

$$\mathrm{SRM}_i = \frac{\theta_i}{\theta_{\mathrm{FC}}} \times 100\% \tag{2}$$

where θ_i is the volumetric SWC of period i, θ_{FC} is field capacity.

CRD can be obtained from the statistics of the precipitation series.

According to the different time of drought, combined with the whole growth period of winter wheat, the drought evaluation period was divided into six stages: sowing–tillering, tillering–wintering, wintering–dial section, dial section–jointing, jointing–heading and heading–mature. The indexes of drought are shown in Table 2.

2.3.1.2. Drought degree and its corresponding adaptive irrigation threshold

In drought conditions, it is an important task to reasonably determine the irrigation threshold for inadequate irrigation. In existing studies, the threshold was mostly determined by given certain value to the upper and lower limits of the SWC based on water stress [24]. For example, Liu et al. [24] pre-defined most of lower thresholds for maize 60% of field capacity based on water stress. A few special techniques are used for irrigation threshold in automated system, such as temperature–time–threshold method developed by Peters and Evett [36], which was based on canopy temperature and time threshold [36].

The effect of water shortage on crop yield may change with its growth stage [7]. Therefore, the irrigation threshold should be determined not only by the plant sensitivity to water stress but also by the dynamic degree of drought that the crop can tolerate in the growing stages. Since the sensitivity coefficient of the crop can reflect the degree of sensitivity of the crop to water stress [37], the threshold should be determined by considering both the sensitivity coefficients of different growth stages and the drought degree of the same period.

In this study, the frequency method was used to determine the drought grade, that is, the occurrence of high frequency of drought as the final comprehensive analysis result. Then the irrigation threshold of each stage is determined based on both the drought degree and crop sensitivity coefficient.

2.3.2. Crops adaptive real-time irrigation approaches

2.3.2.1. Simulation of real-time irrigation

Based on the water balance equation, the daily soil moisture was simulated by:

Table 2
Drought indexes in growth stages of winter wheat

DEI	Growing stage	ED	SD	MD	LD
PPA (%)	Sowing–tillering	≤–68	(–68,–53]	(–53,–35]	(–35,–20]
	Tillering–wintering	≤–73	(–73,–65]	(–65,–45]	(–45,–35]
	Wintering–turning green	≤–73	(–73,–65]	(–65,–45]	(–45,–35]
	Turning green–jointing	≤–65	(–65,–55]	(–55,–35]	(–35,–20]
	Jointing–heading	≤–65	(–65,–55]	(–55,–35]	(–35,–20]
	Heading–maturity	≤–65	(–65,–55]	(–55,–35]	(–35,–20]
CRD (d)	Sowing–tillering	≥35	[28,35)	[16,28)	[10,16)
	Tillering–wintering	≥70	[50,70)	[30,50)	[20,30)
	Wintering–turning green	≥70	[50,70)	[30,50)	[20,30)
	Turning green–jointing	≥23	[18,23)	[15,18)	[10,15)
	Jointing–heading	≥23	[18,23)	[15,18)	[10,15)
	Heading–mature	≥23	[18,23)	[15,18)	[10,15)
SRM (%)	Sowing–tillering	≤40	(40,55]	(55,65]	(65,70]
	Tillering–wintering	≤35	(35,45]	(45,60]	(60,65]
	Wintering–turning green	≤35	(35,45]	(45,60]	(60,65]
	Turning green–jointing	≤40	(40,55]	(55,65]	(65,70]
	Jointing–heading	≤40	(40,55]	(55,65]	(65,70]
	Heading–mature	≤40	(40,55]	(55,65]	(65,70]

Note: DEI, drought evaluation indexes; PPA, percentage of precipitation anomaly; CRD, continuous rainless days; SRM, soil relative moisture; ED, extreme drought; SD, severe drought; MD, medium drought; LD, light drought; ND, no drought.

$$\theta_i = \frac{H_{i-1}}{H_i}\theta_{i-1} - \frac{\left(\mathrm{ET}_{i-1} - P_{0i-1} - M_{i-1} - W_{\mathrm{Ti}}\right)}{\left(1{,}000nH_i\right)} \tag{3}$$

where i is the cumulative days from sowing day (d); M_{i-1} is the irrigation amount on day i–1 (mm); n is the soil porosity (%); H_{i-1} is the effective rooting depth on day i (m).

Assuming that the effective rooting depth increases linearly in each growth stage of the winter wheat growth period, based on the fitted root results of experimental data, the simulated formula of the daily root depth of winter wheat was obtained by the following equation:

$$H_i = h_{n-1} + \left(h_n - h_{n-1}\right)\cdot\left(i - \sum_{j=1}^{n} {}_{j-1}l_{j-1}^{j-1}\right) / l_n^n \tag{4}$$

where h_n and h_{n-1} are the effective rooting depth at the beginning and the end of the nth growing stage, respectively (m); l_n^n and ${}_{j}l_{j}^{j}$ are the total days of growth period n and j, respectively (d). W_{Ti} is the added available soil water in the effective rooting depth from day i–1 to day i, it can be determined as follows:

$$W_{\mathrm{Ti}} = 1{,}000\left(H_i - H_{i-1}\right)\cdot n \cdot \theta_i \tag{5}$$

The crop actual evapotranspiration ET_i (mm d^{-1}) on day i under water stress conditions was calculated by:

$$\mathrm{ET}_i = \mathrm{ET}_{0i}\cdot K_c \cdot K_w \tag{6}$$

where ET_{0i} is the reference evapotranspiration on day i (mm d^{-1}), which can be calculated by the modified Penman equation [38] with meteorological data measured by the AWS; K_c is the crop coefficient, which can be determined by Eqs. (7) and (8) [39]:

$$K_c = 7.346\left(i/I\right)^2 - 1.606\left(i/I\right) + 0.0972 \qquad i/I \le 0.58 \tag{7}$$

$$K_c = -3.463\ln\left(i/I\right) - 0.1909 \qquad i/I \ge 0.58 \tag{8}$$

where I is the total day of whole growth period (d).

K_w is the correction factor of soil moisture. For full irrigation, $K_w = 1.0$; for deficit irrigation, it can be determined by Eqs. (9) and (10) [40]:

$$K_{wi} = \frac{\ln\left(1 + 100\theta_i\right)}{\ln 101} \qquad \theta_{c2} \le \theta_i < \theta_{c1} \tag{9}$$

$$K_{wi} = \alpha \cdot \exp\left[\frac{\left(\theta_i - \theta_{c2}\right)}{\theta_{c2}}\right] \qquad \theta_i < \theta_{c2} \tag{10}$$

where θ_i is the volumetric SWC of day i; θ_{c1} and θ_{c2} are the maximum and minimum irrigation threshold of deficit irrigation, respectively; α is the empirical coefficient, which equals to 0.89 for winter wheat.

Available precipitation can be determined as follows:

$$P_{0i} = \lambda P_i \tag{11}$$

where P_i is the actual precipitation on day i (mm); P_{0i} is the effective precipitation on day i (mm); λ is the effective precipitation utilization factor, which was obtained from Guo [41].

Soil moisture θ_i less than the minimum irrigation threshold $\theta_{\min}$ means winter wheat should be irrigated on day i, and the irrigation amount can be determined by Eq. (12) when the irrigation supply is sufficient:

$$M_i = 1{,}000 \cdot n \cdot H_i \cdot (1 - \theta_i) \tag{12}$$

When the irrigation supply is insufficient, the amount of irrigation can be determined as follows:

$$M_i = 1{,}000 \cdot n \cdot H_i \cdot \left(\theta_{ci} - \theta_i\right) \tag{13}$$

where θ_{ci}

2.3.2.2. Process of adaptive real-time forecast of irrigation schedule

The process of adaptive real-time irrigation schedule was simulated as the following steps:

(1) Assuming the calculation length was i days, θ_i was simulated by Eq. (3) with forecast weather data. In this study, $i = 1$.
(2) Calculating PPA, CRD and SRM, evaluating the drought degree of the coming day using frequency method, and deciding the adaptive real-time irrigation thresholds in the coming day using methodology described in section "Drought evaluation indexes in crop growth season".
(3) Comparing the simulated θ_i with the minimum irrigation threshold θ_{ci} of the coming day, $\theta_i > \theta_{ci}$ shows no irrigation is needed; $\theta_i \leq \theta_{ci}$ shows irrigation would be needed if there is no rain in the coming days and the irrigation amount was calculated by Eqs. (12) or (13); when it will rain during the calculation irrigation period, effective rainfall should be calculated first, if the rainfall is large enough to irrigate and make SWC exceed FC, the part that SWC greater than FC was the final output as excess water infiltrated in deep soil.
(4) Using the measured data θ_i^* as the initial soil water value of stage (i +1), then reaped from steps (2)–(4) till the last day of the whole growing season, and the whole irrigation schedules were obtained.

According to the short-term weather forecast data and soil moisture monitoring data, the drought degree under the changing condition of crop growth season was first evaluated as five grades, and indexes suitable for the drought degree were chosen for determining the irrigation threshold. Second, using field water balance principle and soil moisture simulation technology, adaptive real-time irrigation scheduling was developed to adapt to climate changes and actual rainfall. In the process, the simulation data were corrected by experimental data.

3. Results and discussion

3.1. Drought evaluation during winter wheat growing season

Using frequency methodology, results of drought evaluation in growing season were obtained. Some results of drought degree with 7-d step were shown in Table 3, which revealed that drought occurred frequently during the growing season of winter wheat, especially during the growth stage in March, April and May, which is vigorous growing period of winter wheat. Therefore, irrigation would have a great help on the yield of winter wheat.

Table 3
Partial results of drought degree of winter wheat in 2012–2013

Date	PPA	CRD	SRM	Drought degree
2012/10/21	ND	ND	ND	ND
2012/10/28	ED	ND	ND	ND
2012/11/4	MD	ND	ND	ND
2012/11/25	SD	LD	LD	LD
2012/12/2	ED	LD	LD	LD
2012/12/16	SD	LD	LD	LD
…	…	…	…	…
2013/2/1	ED	ND	ND	ND
2013/3/1	ED	LD	LD	LD
2013/3/8	ED	MD	MD	MD
2013/4/7	MD	SD	MD	MD
2013/4/20	MD	LD	MD	MD
2013/5/12	LD	ND	ND	ND
2013/5/17	ED	MD	MD	MD
2013/5/23	ED	ND	ND	ND

Note: PPA, percentage of precipitation anomaly; CRD, continuous rainless days; SRM, soil relative moisture; ED, extreme drought; SD, severe drought; MD, medium drought; LD, light drought; ND, no drought.

Considering the sensitivity factor of winter wheat in different growth stage, the irrigation thresholds of each growing stage under different drought degree were given in Table 4.

The thresholds in Table 4 indicate that the maximum and minimum of water supply level was coincident with the sensitive index of winter wheat and the drought degree, the values of irrigation thresholds increase with the increase of sensitive index and decrease when the drought degree is higher or severer.

3.2. Daily soil moisture forecasting

Daily soil moisture of root zone is vital for irrigation water balance, and it has a close relationship with irrigation threshold. Therefore, daily soil moisture forecasting is one of the main contents of irrigation scheduling forecast. The comparison between daily soil moisture forecasting and measured soil moisture in whole growing stage among four treatments showed that the forecast results were coincident with the measured soil moisture during the growth season. Comparison between daily soil moisture forecasting and measured SWS of different treatments from March 22 to April 6 was chosen to show the daily soil moisture forecasting results of different treatments (Fig. 2). Most of the forecasting daily SWS among four treatments were close to the measured data and the average relative error was about 1%. For example, under treatment D, the relative error was only 0.41% on March 30 with the measured and forecasting SWS was 25.17% and 25.28%, respectively. While for the forecasting SWS on April 3 under treatment

Table 4
Irrigation thresholds in growing stages of winter wheat

Growth stage	Sensitivity coefficient[a]	ED (% FC)	SD (% FC)	MD (% FC)	LD (% FC)
Sowing–tillering	0.1156	60–75	60–75	60–80	60–85
Tillering–wintering	0.1146	60–70	60–70	60–75	60–80
Wintering–turning green	0.1105	60–70	60–70	60–75	65–75
Turning green–jointing	0.3148	60–75	60–85	60–85	65–85
Jointing–heading	0.2454	60–75	60–85	65–90	70–90
Heading–mature	0.0001	60–65	60–65	60–70	60–70

Note: FC, field capacity; ED, extreme drought; SD, severe drought; MD, medium drought, LD, light drought; ND, no drought.
[a] Sensitivity coefficients came from the data at Agricultural Irrigation Experimental Station of Farmland Irrigation Research Institute, China.

C, there was individual anomalies, the relative error was 7.67% with the measured and simulated SWS was 20.53% and 22.10%, respectively, which was much larger than the average relative error, but still less than the required precision of 10%. The larger gap between the forecasting and measured values may be caused by a precipitation of less than 5 mm before April 3, and the effective rainfall for this small rainfall during the period of simulation would result in an error accumulation between the simulated and the measured value. Those comparisons between the measured and simulated values of soil moisture in growth of winter wheat lead to the conclusion that the methodology was available for adaptive real-time irrigation.

3.3. Irrigation scheduling for winter wheat

3.3.1. Adaptive irrigation scheduling for winter wheat

Winter wheat of different treatments was irrigated based on the real-time irrigation model in this study. The results of real-time irrigation scheduling for winter wheat in 2012–2013 and 2013–2014 growing season were shown in Table 5, including irrigation amount, irrigation date and irrigation times.

Results in Table 5 show obvious difference among four experimental treatments. Under treatment A, the lower limit of irrigation was 80% FC, which was higher than other treatments and almost near sufficient irrigation. There was six irrigation times during each growing season of 2012–2013 and 2013–2014: once during sowing–tillering stage, twice during tillering–wintering stage, twice during dial section–jointing and once during jointing–heading stage. Irrigation amount was the most among different treatments, and total irrigation amount was 269 mm in 2012–2013 and 266 mm in 2013–2014, respectively.

Total irrigation amounts of treatments B and C were much less than that of treatment A, which may be due to treatments B and C were limited irrigation. Total irrigation amount of B treatment was 142 mm in 2012–2013 and 141 mm in 2013–2014, which takes up about 53% of treatment A. On the other sides, total irrigation amount of treatment C was 124 mm in 2012–2013 and 114 mm in 2013–2014, accounting for 46% and 43% of treatment A, respectively. Much less irrigation water was needed under treatment B and C.

Under treatment D, irrigation was changed in accordance with the drought condition. There was an obvious difference between the irrigation amount during 2012–2013 and 2013–2014. Total irrigation amount was similar to that of treatment A in 2012–2013, even the irrigation threshold of A and D were different. The total irrigation was 262 mm, just less 69 mm than treatment A. According to the precipitation in 2012–2013, rainfall was less in growing season and it is reasonable that more irrigation to be needed to reach higher yield. The total irrigation amount in 2013–2014 growing season dropped a lot compared with that of 2012–2013. Winter wheat during 2013–2014 should be irrigated five times and the total amount was 177 mm, less 85 mm than the year before. Less irrigation during 2013–2014 was mainly because that rainfall in 2013–2014 was much larger than that in 2012–2013, and the water demand of winter wheat in 2013–2014 can be more supplemented by rainfall than that in 2012–2013.

There is no much difference among the total irrigation water amount of treatment A, B or C between different years. The total irrigation amount of D treatment is big different compared with the former, mainly because the irrigation threshold was decided based on both the degree of drought and the use of rainwater. In the four treatments, strategy D was not the most water-saving treatment, but it could adapt to weather change and used the rainfall effectively.

3.4. Effect of adaptive irrigation on crop yield

Crop water productivity (WP, kg m^{-3}) is a vital index to measure the water input and crop output efficiency, usually be used to judge the efficiency of water-saving irrigation. It can be obtained as follows [50]:

$$\mathrm{WP} = \frac{Y}{\left(W_n + P_0 + g_s\right)} \tag{14}$$

where Y is net crop yield (kg hm^{-2}); P_0 is effective precipitation (m^3 hm^{-2}); g_s is groundwater supply (m^3 hm^{-2}), for this study, it was 0 for the groundwater depth is greater than 3 m in the experimental plots; W_n is net irrigation amount, which can be simulated as follows:

$$W_n = \eta \cdot \sum_{i=1}^{n} M_i \tag{15}$$

Table 5
Irrigation schedule for winter wheat in 2012–2013 and 2013–2014 under different treatments

Year	Irrigation schedule	Treatment A	Treatment B	Treatment C	Treatment D
2012–2013	Irrigation date	25 Oct.; 28 Nov.; 14 Mar.; 8 Apr.; 24 Apr.; 16 May	21 Mar.; 4 Apr.; 6 May	19 Apr.; 7 May	25 Nov.; 2 Jan.; 15 Mar.; 29 Mar.; 12 Apr.; 26 Apr.; 10 May; 17 May
	Irrigation amount (m^3 ha^{-1})	238; 270; 449; 511; 589; 628	354; 441; 623	572; 665	151; 196; 235; 352; 409; 387; 502; 385
	Irrigation times	6	3	2	8
	Total irrigation amount (m^3 ha^{-1})	2,685	1,418	1,236.67	2,617
2013–2014	Irrigation date	27 Oct.; 22 Nov.; 8 Mar.; 1 Apr.; 24 Apr.; 14 May	18 Mar.; 3 Apr.; 9 May	2 Apr.; 5 May	5 Jan.; 2 Apr.; 16 Apr.; 10 May; 27 May
	Irrigation amount (m^3 ha^{-1})	227; 255; 449; 562; 567; 602	357; 471; 580	492; 650	199; 320; 417; 485; 349
	Irrigation times	6	3	2	5
	Total irrigation amount (m^3 ha^{-1})	2,662	1,408	1,142	1,769

where η is irrigation water utilization factor, for the experiments, η was 0.85; n is the total irrigation time; M_i is the irrigation amount of each time ($m^3 hm^{-2}$).

According to different field experimental results, WP of each treatment in growth season of 2013–2014 can be seen in Table 6.

Results in Table 6 show that WP of winter wheat does not increase with the increase of irrigation amount. Crop yield under treatment A was 6,542 kg hm^{-2} which was the highest among the four treatments, but its total irrigation amount was also the largest, WP was only 1.83 kg m^{-3}, so treatment A is not optimal under limited agriculture water, which is in agreement with the conclusion of the studies by Li et al [42]. Though crop yield under treatment B was less 94 kg hm^{-2} than that of treatment A, the irrigation amount is also less 13 m^3 than treatment A and only takes up 53% of that under treatment A, the WP of treatment B was 2.25 kg m^{-3} and it was the highest among four treatments, which means treatment B is the best for water saving. Crop yield and WP under treatment C were both the least one, which was mainly due to the lower minimum water supply, which hindered the crop growth. Yield of treatment D was 6,038 kg hm^{-2}, which was less 504 kg hm^{-2} than treatment A but larger 390 kg hm^{-2} than treatment B. Irrigation amount of treatment D was less 9.26 m^3 than that of treatment A and extra larger 3.53 m^3 than that of treatment B, its WP was the second highest, which revealed its effective water saving.

4. Discussion

Irrigation is necessary during winter wheat growing season in North China and how to allocate limited agricultural water in arid conditions is very important. Field experiments from 2011 to 2014 showed that winter wheat needs a lot of irrigation. The average irrigation amount of different irrigation treatments was 262 mm in 2012–2013 and 177 mm in 2013–2014 growing season, respectively.

For traditional irrigation in China, typical hydrology annual precipitation was often used to plan irrigation

Table 6
Water productivity of winter wheat under different experimental treatment

Treatment	Gross irrigation amount (m^3)	Net irrigation amount (m^3)	Effective precipitation (mm)	Crop yield (kg ha^{-1})	WP (kg m^{-3})
A	31.94	27.15	131.06	6,542	1.83
B	16.89	14.36	131.06	5,648	2.25
C	13.71	11.65	131.06	3,349	1.47
D	21.05	17.89	131.06	6,038	2.15

Note: WP, water productivity.

schedule for future years. There are significant differences between the coming year and the typical year for the uncertainty and diversity of the rain, so the planned irrigation schedule always cannot be used in practice. In addition, when irrigation occurred before a rain, traditional irrigation without regarding to weather forecasts sometimes would result in the waste of limited water resources. In this study, meteorological forecast data were used to determine the irrigation strategy, which can enhance the use of rainfall [23].

Real-time irrigation is a new technique to improve rainfall utilization in recent years. In most studies, the threshold of irrigation is always set to a constant value, and the lower limit of the irrigation threshold is generally set to 60% FC or 65% FC [24]. For the response of different crop growth stage to water deficit is usually different, irrigation schedule should be changing with different weather conditions to improve water efficiency, especially in drought season under limited water condition.

Water should be allocated based on dynamic judgment for drought degree, which has been reported by a typical hydrology irrigation model [15]. In some sensitive crop growth stage, higher levels of drought will lead to more severe water stress and lower yields. Based on extensive reviews of the literature, few studies on adaptive real-time water-saving irrigation based on dynamic drought assessment have been found, especially in North China.

Irrigation thresholds are essential for water allocation. Usually irrigation threshold was decided by experience. This paper presents a new method called adaptive irrigation system to decide the irrigation threshold. The threshold of irrigation was decided by the drought degree of the coming days and the crop sensitive coefficient of the growing season (Table 4). The similarity between the simulation and measured data shown in Fig. 2 indicated the adaptive irrigation schedule worked reasonable. Results in Table 6 indicated that there is a much increase of yield in the adaptive irrigation. The big gap may be that the adaptive irrigation could fully use the rainfall according to the change of weather and get a higher WP. Those results would suggest that the methodology and process were somewhat successful.

In order to find a way to fully use irrigation water and rainfall under limited available water to minimise the influence of water shortage on yield, a new method, which closely relating the irrigation threshold both to the crop sensitive coefficient and drought degree of coming days, is established in this study. There are still some more researches to do further. For example, the suitable irrigation threshold values including the upper and the lower limit should be exactly determined based on the analysis of the accurate relationship between irrigation threshold and the drought degree, and sensitive coefficient should

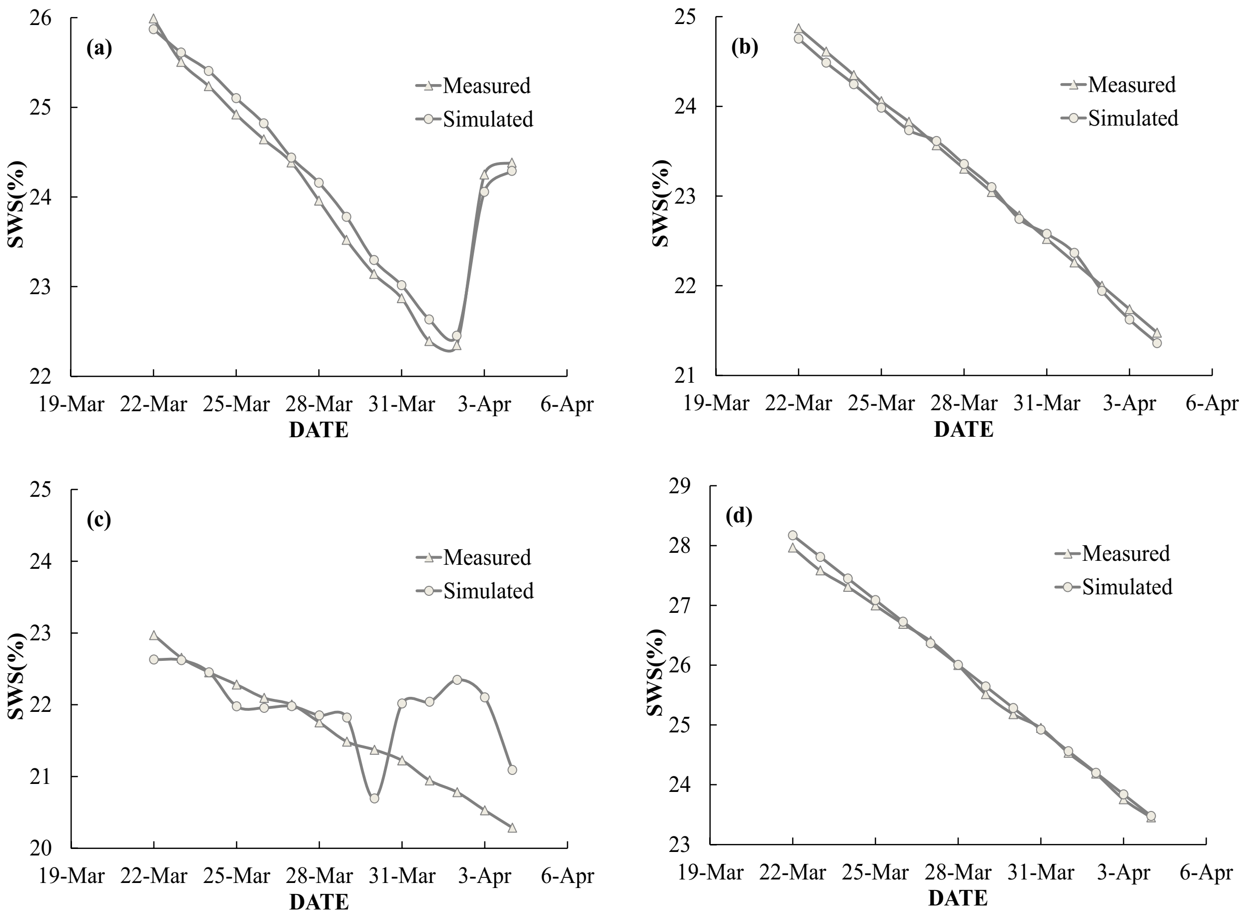

Fig. 2. Comparison of simulated soil moisture and measured ones under 4 treatments in 2011–2012 growth period.

be more exactly based on bio-ecological character of crop. In addition, further studies should use the daily K_c instead of the mean K_c stage value to determine the threshold.

5. Conclusions

Mainly aimed to use limited irrigation water efficiently, this paper provides an adaptive process for optimal allocation of irrigation water in response to the coming drought. Results showed that the method could help not only to resolve irrigation allocation but also to give path of fully using precipitation. Results can be concluded from the works as followings:

Winter wheat was selected to use the adaptive real-time irrigation scheduling from 2011 to 2014. The measured soil moisture and forecast meteorology data were used to compare the traditional irrigation treatments with adaptive irrigation treatment: treatment A, which is full irrigation, had the highest yield but a lower WP; treatment B had the highest WP and its yield was lower than treatment A but higher than the other two treatments. Both the yield and WP of treatment C were the lowest, and treatment D, which is adaptive irrigation, had a relative high yield and WP.

Extra comparisons include measured and simulated SWS of growing season among the four treatments indicated that treatment B was the strategy for enhanced water usage efficiency and water allocation, could help for sustainable development of limited irrigation water. Whereas treatment D, based on weather changes had a relative high irrigation usage efficiency, was the second highest among four treatments; treatment D could make irrigation decisions adjusting to weather changing, make good irrigation guide based on present hydrology for farmers.

Adaptive irrigation scheduling was different from traditional irrigation, its input data were forecast meteorology data and real-time measured data, it could make full use of precipitation and solve real-time irrigation allocation problems, which could give irrigation guide for farms to make irrigation plan.

The adaptive real-time irrigation schedule based on drought evaluation is a new method. Though the irrigation threshold is still needed to be further studied, it is more suitable for application in winter wheat in North China to cope with the limited water resources of the irrigation districts.

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References

[1] I. Simmers, Hydrological Processes and Water Resources Management, I. Simmers, Ed., Understanding Water in a Dry Environment: Hydrological Processes in Arid and Semi-arid Zones, Balkema Publishers, Rotterdam, The Netherlands, Vol. 1, 2003, pp. 1–14.

[2] IPCC, T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P.M. Midgley, Eds., The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom, 2013, pp. 1–1535.

[3] J.M. Peragón, F.J. Pérez-Latorre, A. Delgado, A GIS-based tool for integrated management of clogging risk and nitrogen fertilization in drip irrigation, Agric. Water Manage., 184 (2017) 86–95.

[4] G. Fischer, F.N. Tubiello, H. Van Velthuizen, D.A. Wiberg, Climate change impacts on irrigation water requirements: effects of mitigation, 1990–2080, Technol. Forecast. Soc. Change, 74 (2007) 1083–1107.

[5] L. Liu, J. Ma, Y. Luo, C. He, T. Liu, Hydrologic simulation of a winter wheat–summer maize cropping system in an irrigation district of the lower Yellow River Basin, China, Water, 9 (2017), doi: 10.3390/w9010007.

[6] S. Mushtaq, D. Dawe, H. Lin, P. Moya, An assessment of the role of ponds in the adoption of water-saving irrigation practices in the Zhanghe irrigation system, China, Agric. Water Manage., 83 (2006) 100–110.

[7] Z.Y. Dai, Y.P. Li, A multistage irrigation water allocation model for agricultural land-use planning under uncertainty, Agric. Water Manage., 129 (2013) 69–79.

[8] E. Fereres, M.A. Soriano, Deficit irrigation for reducing agricultural water use, J. Exp. Bot., 58 (2007) 147–159.

[9] B. Grove, L.K. Oosthuizen, Stochastic efficiency analysis of deficit irrigation with standard risk aversion, Agric. Water Manage., 97 (2010) 792–800.

[10] S. Kang, L. Zhang, Y. Liang, W. Dawes, Effects of limited irrigation on yield and water use efficiency of winter wheat in the Loess Plateau of China, Agric. Syst., 78 (2003) 355–367.

[11] Y. Huang, Y.P. Li, X. Chen, Y.G. Ma, Optimization of the irrigation water resources for agricultural sustainability in Tarim River Basin, China, Agric. Water Manage., 107 (2012) 74–85.

[12] E. Fereres, D.A. Goldhamer, Suitability of stem diameter variations and water potential as indicators for irrigation scheduling of almond trees, J. Hortic. Sci. Biotechnol., 78 (2003) 139–144.

[13] H.G. Jones, Irrigation scheduling: advantages and pitfalls of plant-based methods, J. Exp. Bot., 55 (2004) 2427–2436.

[14] Y.S. Chauhan, G.C. Wright, D. Holzworth, C.N.R. Rao, J.O. Payero, AQUAMAN: a web-based decision support system for irrigation scheduling in peanuts, Irrig. Sci., 31 (2013) 271–283.

[15] S. Chen, J. Ma, L. Qiu, Fuzzy optimization of multi-dimensional multi-objective dynamic programming and its application to farm irrigation, J. Hydraul. Eng., 33 (2002) 33–38.

[16] N.H. Rao, P. Sarma, S. Chander, Irrigation scheduling under a limited water supply, Agric. Water Manage., 15 (1988) 165–175.

[17] Z. Shangguan, M. Shao, R. Horton, T. Lei, L. Qin, J. Ma, A model for regional optimal allocation of irrigation water resources under deficit irrigation and its applications, Agric. Water Manage., 52 (2002) 139–154.

[18] L. Wang, L. Fang, K.W. Hipel, Basin-wide cooperative water resources allocation, Eur. J. Oper. Res., 190 (2008) 798–817.

[19] R.D. Gear, M.D. Campbell, A.S. Dransfield, Irrigation scheduling with neutron probe, J. Irrig. Drain. Div., 103 (1977) 291–298.

[20] D.R. Maidment, P.D. Hutchinson, Modeling water demands of irrigation projects, J. Irrig. Drain. Eng., 109 (1983) 405–418.

[21] R.C.G. Smith, J.L. Steiner, W.S. Meyer, D. Erskine, Influence of season to season variability in weather on irrigation scheduling of wheat: a simulation study, Irrig. Sci., 6 (1985) 241–251.

[22] B.A. George, B.R.S. Reddy, N.S. Raghuwanshi, W.W. Wallender, Decision support system for estimating reference evapotranspiration, J. Irrig. Drain. Eng., 128 (2002) 1–10.

[23] N.G. Inman-Bamber, S.J. Attard, S.A. Verrall, C. Baillie, A web-based system for scheduling irrigation in sugarcane, Proc. Int. Soc. Sugar cane Technol., 26 (2007) 459–464.

[24] Y. Liu, J.L. Teixeira, H.J. Zhang, L.S. Pereira, Model validation and crop coefficients for irrigation scheduling in the North China plain, Agric. Water Manage., 36 (1998) 233–246.

[25] J.Q. Ma, Z.W. Zhang, M. Xu, A Fuzzy Cluster Method for Real-time Water Demand in Unsurveyed Irrigation Area, 2010 3rd International Conference on Biomedical Engineering and Informatics, Yantai, China, 2010, pp. 16–18.

[26] C.L. Fernandez, T.N. Trolinger, Development of a web-based decision support system for crop managers: structural consideration and implementation case, Agron. J., 99 (2007) 730–737.

[27] J.Q. Ma, W.Z. Wang, Soil moisture on-line forecasting and real-time irrigation schedule model for winter wheat, Water Resour. Power, 10 (2013) 139–141+188.

[28] J. Ma, L. Liu, Z. Zhang, X. Hao, G. Peng, Real-time Irrigation Theory and Integrated Management System for Agricultural Water Resources, China Water Conservancy and Hydropower Press, Beijing. 2013, pp. 73–75.

[29] J. Keyantash, J.A. Dracup, The quantification of drought: an evaluation of drought indices, Bull. Am. Meteor. Soc., 83 (2002) 1167–1180.

[30] A. Dai, K.E. Trenberth, T. Qian, A global dataset of palmer drought severity index for 1870–2002: relationship with soil moisture and effects of surface warming, J. Hydrometeorol., 5 (2004) 1117–1130.

[31] R.R. Heim, A review of twentieth-century drought indices used in the United States, Bull. Am. Meteor. Soc., 83 (2002) 1149–1165.

[32] General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Standardization Administration of People's Republic of China, National Standard of the People's Republic of China: Grades of Meteorological Drought GB/T 20481-2017, Standards Press of China, 2017, pp. 2–3.

[33] Ministry of Water Resources of People's Republic of China, Standard of Ministry of Water Resources of People's Republic of China: Standard of Classification for Drought Severity SL424-2008, China Water Power Press, 2008, pp. 6–12.

[34] J. Wei, Z. Ma, Comparison of palmer drought severity index, percentage of precipitation anomaly and surface humid index, Acta Geogr. Sinica, 52 (2003) 1–8.

[35] Z. Ma, C. Fu, Trend of surface humid index in the arid area of northern China, Acta Meteorol. Sinica, 59 (2001) 737–746.

[36] R.T. Peters, S.R. Evett, Automation of a center pivot using the temperature-time-threshold method of irrigation scheduling, J. Irrig. Drain. Eng., 134 (2008) 286–291.

[37] H. Zhang, T. Oweis, Water-yield relations and optimal irrigation scheduling of wheat in the Mediterranean region, Agric. Water Manage., 38 (1999) 195–211.

[38] R.G. Allen, L.S. Pereira, D. Raes, M. Smith, Crop Evapotranspiration: Guidelines for Computing Crop Requirements. Irrigation and Drainage paper No 56. Food and Agriculture Organization of the United Nations, Rome, 1998, pp. 1–15.

[39] B. Liu, X. He, S. Pu, W. Zhang, Framework design for real-time irrigation dispatching system, China Water Resour., 15 (2007) 50–52.

[40] S.X. Gu, Y.H. Li, H.Y. Yuan, Real time forecasting of crop evaportranspiration of Huoquan irrigation district, J. Wuhan Univ. Hydraul. Electr. Eng., 31 (1998) 37–41.

[41] Y. Guo, Irrigation and Drainage Engineering, China Water Conservancy and Hydropower Press, Beijing, 1997, p. 41.

[42] J. Li, S. Inanaga, Z. Li, A.E. Eneji, Optimizing irrigation scheduling for winter wheat in the North China Plain, Agric. Water Manage., 76 (2005) 8–23.