Impact Of Drip And Level Basin Irrigation On Growth And Yield Of Winter Wheat In The North China Plain

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ABSTRACT

Optimum irrigation water management is essential to sustain high winter wheat (*Triticum aestivum* L.) yields and to increase its water-use efficiency (WUE) in view of the serious constraints in the water-resource situation in the North China Plain (NCP). A field experiment was conducted for 3 consecutive years (2007-2009) to study the effects of different irrigation methods and schedules on crop growth, yield and WUE of winter wheat (*Triticum aestivum* L.) in the NCP. In this research work, water-saving irrigation methods, including the level-basin irrigation (BI) and drip irrigation (DI), were selected, and four irrigation schedules were designed for BI and DI methods, respectively. These initiated irrigation at 25%, 40%, 50% and 60% of water depletion of the field capacity (FC) across the reviving to booting growth stages, was designated as B1, B2, B3 and B4 for the BI method and D1, D2, D3 and D4 for the DI method, respectively.

The results indicate that irrigation methods and schedules had globally significant effects on crop growth and yield of winter wheat. The total irrigation amount or irrigation schedules significantly influenced plant heights and LAI ($P_{0.05}$ level), and irrigation amount or irrigation schedules also had significant effects on winter wheat grain yields ($P_{0.05}$ level) for both irrigation methods, and there were no statistically significant differences in terms of average yields and mean WUE for the adequate irrigation treatments under both irrigation methods ($P_{0.05}$ level). Further, the DI method had a significant advantage of improving yield and WUE compared with the BI method ($P_{0.05}$ level) under the condition of deficit irrigation and no significantly different seasonal ET. In addition, without irrigation system investment consideration, the D3 treatment or 326 mm seasonal ET was recommended for winter wheat irrigation in the NCP, which saved 35% irrigation water meanly during 2007-2009 with only 13% decrease in winter wheat yield compared with B1, and the optimum controlled soil water content at effective rooting depth range in this study for winter wheat irrigation in the NCP was: 50% FC-75% FC at the reviving to booting growth period, 75% FC-FC at booting to heading stage and 55% FC-70% FC at the milking to maturity stage.

Key words: Winter wheat (Triticum aestivum L.); drip irrigation; level basin irrigation; irrigation schedule; water use efficiency

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1. Introduction

The North China Plain (NCP) forms part of the most important food production area in China. In this region, winter wheat (*Triticum aestivum L.*) is a major crop and its food production accounts for approximately 71% of wheat production in China (Liu and Lin, 2004).

In the NCP, annual precipitation is extremely variable and ranges from 300 to 1000 mm, with an average of approximately 500 mm (Zhang and You, 1996). However, the temporal distribution of annual rainfall in the NCP is extremely variable, with more than 70% concentrated in the maize growing season (July to September). In the winter wheat-growing season (from October to the following June), the precipitation is approximately 60-150 mm (Zhang et al., 2003), and evapotranspiration (ET) is approximately 450 mm (Liu et al., 2002). As a consequence, irrigation is essential to maintain high winter wheat yields and to increase its water-use efficiency (WUE) significantly (Ehdaie, 1995; Li et al., 1999; Deng et al., 2002).

According to certain data, water used for field irrigation accounts for 80% of the total water use in the NCP; the water used for winter wheat irrigation accounts for 70% of water used for field irrigation (Li et al., 2005). Therefore, development of optimum water managements (Zhang and You, 1996; Manoliadis, 2001) is an urgent necessity to avoid further over-exploitation of groundwater and for a sustainable crop production (Li, 1993; Manoliadis, 2001；Zhang et al., 2003).

In recent years, limited or deficit irrigation methods have been well studied and widely practiced for improving crop yield and WUE; however, most of these studies have only focused on the effect of irrigation scheduling in a type of irrigation method on winter wheat yield and WUE (Schneider and Howell,1997; Zhang et al., 1998; Zhang et al., 1999; Zhang and Oweis,1999; Li et al., 2000; Kang et al., 2002; Li et al., 2005). In addition, studies conducted on irrigation demand management often focus only on irrigation scheduling (Endale and Fipps, 2001), and pay minimal attention to irrigation methods. Similarly, research on crop responses to irrigation and water productivity that was conducted in China, often, did not consider constraints relative to the irrigation method (Huang, 2000; Liu et al., 2002; Wang et al., 2001). A combined approach is required (Pereira, 1999; Pereira et al., 2002) for more accurate information on irrigation requirements.

Water-conserving irrigation methods, including level-basin irrigation (Li and Calejo, 1998), drip irrigation and sprinkler irrigation and so on, have gradually gained worldwide popularity with the increasing shortage of water resources. These water-conserving irrigation methods are primarily being applied for cash crops or sparse row crops, such as corn, tomato and cotton. However, applications on fields of dense crops, such as wheat have been few or absent due to the high installation and management costs involved. Therefore, recent studies have also focused attention on the effects of different water-conserving irrigation methods on cash crop yield and WUE（Hanson et al., 1997; Yohannes and Tadesse,1998; Al-Jamal et al., 2001; Cetin and Bilgel, 2002; Singandhupe et al., 2003; Antony and Singandhupe,2004）.

As noted above, a combined approach, considering both irrigation schedule and method, is required for an optimal irrigation model. The water-resource situation has been becoming increasingly serious in the NCP; therefore, there is a need for adopting water-conserving irrigation methods and optimum irrigation schedule for food crop irrigation（Shan et al., 2002; Kang, 2003）. A deficit irrigation schedule provides a means of reducing water consumption while minimizing adverse effects on the yield (English and Nakamura, 1989; English and Raja, 1996; Mugabe and Nyakatawa, 2000; Ghinassi and Trucchi, 2001; Zhang et al.,2004, Deng et al., 2006); further, appropriate water deficit during certain growth stages can be helpful to increase yield and WUE (Asseng et al., 1998; Plant et al., 1998). Nonetheless, the deficit irrigation schedule has been adopted for field food crops for a few years now, and the optimum deficit stage and amount for food crops has not been standardized as yet (Cai et al., 2000).

This study investigated the effects of irrigation schedules and different water-conserving irrigation methods, including level-basin irrigation and drip irrigation on the yield and WUE of winter wheat in the NCP. Therefore, this study aimed to identify the best irrigation-management technique (in terms of irrigation methods and schedule) for food crops and to provide useful guidelines to farmers or irrigation managers in the NCP on optimizing limited irrigation schedules for high-yield wheat production.

2. Materials and methods

2.1 Experimental site

Field experiments with winter wheat (*Triticum aestivum* L.) were carried out at the Irrigation Experiment Station of the China Institute of Water Resources and Hydropower Research (IWHR) at Daxing, south of Beijing (39°39′ N latitude, 116°26′ E longitude). The climate in the experimental site varies between semiarid and sub-humid weather conditions, with a cold and dry winter and a hot and humid summer, during which the monsoon rains arrive. The soil in this region of the North China Plain is a silty soil formed by deposits of the loess formations (Cai et al., 2009). The primary soil hydraulic properties are presented in Table 1. The soil in the experimental area was a silt loam, with average field capacity (FC) and bulk density of 0.306 $m^3\ m^{-3}$ and 1.58g cm^{-3} in the crop root zone (1 m depth). The FC was measured in the laboratory as the soil water content at a specific suction pressure of 33 kPa.

Table 1. Physical properties of the soil at the experimental site

Soil depth(cm)		0-20	20-40	40-60	60-80	80-100
Particle size(%)	<0.002mm	10.83	11.67	16.17	16.17	16.17
	0.05-0.002mm	45.57	43.17	40.97	43.17	37.83
	1-0.05mm	43.67	45.17	42.86	40.67	46.00
Bulk density (g/cm^3)		1.36	1.65	1.63	1.67	1.61
Field capacity (vol%)		28.73	30.17	31.49	30.55	31.98

2.2. Irrigation and treatment design

Field experiments with winter wheat (*Triticum aestivum* L.) were conducted for three growing seasons (2006/2007, 2007/2008 and 2008/2009). Water-conserving irrigation methods, including level-basin irrigation (BI) and drip irrigation (DI) were selected for field experiments, and each irrigation method was arranged according to four irrigation schedules; specifically, eight irrigation treatments consisting of two factors: irrigation methods and irrigation schedules were employed (details in Table 2) for field experiments with winter wheat for three consecutive growing seasons. The experimental design was applied by using split plots in randomized blocks with three replications for each treatment. Every plot measured 4.5 × 5 m, and was separated by 0.6-m wide non-irrigated alleys; these plots were bordered with earth dikes to ensure there was no run off.

Irrigation water was pumped from a deep well near the experimental field, and conveyed by plastic pipes, which could be connected or dismantled. A soft plastic pipe was used directly for level-basin irrigation. For the drip-irrigation treatments, a drip irrigation system was set up and usually comprised a filter system, a fertilizer system, pressure gauges, PE manifold pipelines, PE laterals and so on. Each drip irrigation treatment was operated by a control valve. Drip irrigation laterals measured 16 mm in diameter. The drippers were the inline type, placed 0.3-m apart, with a 1.1 liter/h flow rate at 10 m of operating pressure; this was selected from the “Typhoon” series of the Netafim Company. The space between drip lines was 0.5 m, conforming with the row spacing of winter wheat.

A flow meter was used to control the amount of water applied for each treatment. Prior to preparation of the experimental land, 67 mm of irrigation was applied for all treatments. Pre-sowing irrigation, which is widely employed in the NCP, is necessary for promoting seed emergence and ensuring normal growth of seedlings; it also helps to facilitate the arrangement of experimental treatments. The growing season of winter wheat was divided into four phases that were considered most relevant from the viewpoint of their response to irrigation, i.e. phase 1: reviving to jointing; phase 2: jointing to booting; phase 3: booting to heading; and phase 4: milking to maturity.

Eight irrigation treatments, consisting of two factors—irrigation methods and irrigation schedules—were employed (details in Table 2) for three consecutive years (2007-2009) during the growing season of winter wheat. For avoiding winter injury, 67 mm of irrigation was applied during mid-December for all treatments. In this study, the irrigation scheduling arrangements from growing phase 3 to phase 4 of winter wheat were the same for all treatments, established with reference to the experience reported for relevant research (Chen et al., 1995; Cai et al., 2000; Zhang et al., 2001; Zhang et al., 2002; Shi, 2006; Zhang et al., 2006); and these research works were carried out with an aim to determine the optimal irrigation schedule for winter wheat in the NCP. The different irrigation scheduling arrangements were mainly appeared from growing phase 1 to phase 2 of winter wheat, which still had no recognized regular pattern. Irrigation scheduling was based on the soil-moisture deficit in the effective root zone at each irrigation event (difference between effective root zone soil water at the upper limit and at irrigation time) in each treatment. When the soil moisture in the effective root zone reached the designated lower limit, water was applied up to the designated upper limit range. The amount of irrigation water applied in the BI and DI methods in each irrigation event to replace the soil water deficit was calculated as (Chen et al., 1995):

$$I = H(\theta_{up} - \theta_0) p_w / \eta \tag{1}$$

where I is the application amount (mm); H is the effective rooting depth (mm); θ_{up} is the volumetric water content at the upper limit of a treatment during certain growth stages (%); θ_0 is the average volumetric water content in the effective rooting depth at the time of irrigation (%)； p_w is the percentage of wetted area (for drip irrigation and level-basin irrigation, this was assumed to be 60% and 100%, respectively); and η is the application efficiency (for drip irrigation and level-basin irrigation, this was assumed to be 90% and 80%, respectively).

As shown in table 2, for the same irrigation method, the difference of irrigation schedules for different treatments appeared mainly at the reviving to jointing and jointing to booting phases of winter wheat. Water application was initiated when the average volumetric water content at effective rooting depth range (0-60cm) coincided with 40%, 50%, 60% and 75% of field capacity (FC) for four different treatments, respectively; this was also designated as the lower limit indicator for initiation of irrigation. During other growth phases, including the booting-to-heading and milking-to-maturity stages, the effective rooting depth was considered to be 80 cm (Chen et al., 1995). For the same irrigation method, irrigation schedules were the same for four different treatments, and minimum water stress was maintained during the critical phases of crop growth, such as the booting-to-heading stage, to ensure that the winter wheat yield was not affected adversely. In addition, during the milking-to-maturity phase, the soil water content could be maintained at a medium deficit condition, which was adopted following a review of relevant research results.

Table 2. Irrigation methods and schedules in the various treatments during 2007-2009 growing seasons of winter wheat in the NCP

treatments	Irrigation scheduling (soil water content lower to upper limit)			
	Reviving to jointing	Jointing to booting	Booting to heading	Milking to maturity
B1/D1	75% FC—FC	75% FC—FC	75% FC—FC	55% FC—70% FC
B2/D2	60% FC—FC	60% FC—FC	75% FC—FC	55% FC—70% FC
B3/D3	50% FC—75% FC	50% FC—75% FC	75% FC—FC	55% FC—70% FC
B4/D4	40% FC—60% FC	40% FC—60% FC	75% FC—FC	55% FC—70% FC

Note: B1, B2, B3 and B4 refer to the four treatments of level-basin irrigation, respectively; D1, D2, D3 and D4 refer to the four treatments of drip irrigation, respectively; for B1 and D1 treatments, there are no differences for irrigation lower and upper limits during the same growth phase; and B2 and D2, B3 and D3, B4 and D4 is so.

2.3 Crop management

Winter wheat (*Triticum aestivum* L. cv. Zhongmai 9) was sown on 13 October 2006, 12 October 2007 and 15 October 2008, at a row spacing of 25 cm. Seedling density after germination was approximately 500–600 plants/m^2. For all treatments, winter wheat was sown at mid-October and harvested in mid-June of the following year. To help germination and establishment, the winter wheat in each plot was also irrigated with approximately 67 mm of water once prior to sowing (October 10, 2006; October 9, 2007; October 12, 2008) and once prior to the winter freeze (December 12, 2006; December 10, 2007; December 11, 2008).

For each level-basin irrigation plot, 330 kg/ha of urea was scattered manually prior to the first irrigation during the reviving to jointing phase of winter wheat; for each drip irrigation plot, 330 kg/ha urea was applied by injecting into a fertilizer tank connected to the drip irrigation systems. In addition, weed, diseases and insect control were uniformly managed during the winter wheat-growing seasons.

2.4 Measurement of soil water and water use

The soil moisture content was measured on every alternate day as well as immediately prior to each irrigation application during the crop experiment. For each BI treatment plot, a time domain reflectometry (TDR) tube probe (IMKO, Germany, TRIME-FM/T3C) was used for monitoring volumetric soil-water content. Measurements were recorded by inserting the TDR tube probe into the TRIME access tubes that were installed at the center of the plots to a depth of 1 m prior to winter wheat sowing, and measurements were performed at 20-cm intervals down to 100 cm. The TDR tube probe was calibrated onsite by determining volumetric water content (cm^3/cm^3) from direct soil sampling prior to winter wheat sowing, as recommend in the user manual (Imko, 2001). For each DI treatment plot, soil samples were taken at positions directly under the drippers at soil depth ranges of 0-20, 20-40, 40-60, 60-80, and 80-100 cm; soil water content was determined by the gravimetric method and was converted to a percentage volumetric basis by multiplying the values by the bulk density of the soil of the respective layer.

2.5 Measurement of plant heights, leaf area index, grain yield and estimation of WUE

The growth of the crop was measured by means of plant height and leaf area index, which were recorded in periodic sampling throughout the growth period. The plant height of wheat was measured by a ruler; for measurement of the leaf area index (LAI), we strictly followed the procedure designed by Duchemin (2006), i.e. on each of the 24 fields, at regular intervals of 2-3 weeks, two to five small square "plots" (i.e. elementary area of 0.25 m^2 = 0.5m × 0.5 m) were sampled. On each plot, the leaf density was derived from the plant density and the average number of green leaves per plant. In a second step, five plants were selected at random to measure the size of each leaf, i.e. the length (L) and width (W) of a rectangle that encompasses the leaf. The average leaf area was estimated as the product of the mean leaf size (L × W) and a reduction coefficient based on the leaf shape (0.87 for wheat after Ledent (1976)). The average leaf area was multiplied by the leaf density to calculate the LAI on each plot.

The GY (grain yields) of winter wheat was sampled from the 2 × 2 m portion in the central area of each plot, and grains were sun-dried until they had a water content of approximately 10%. Finally, water-use efficiency (WUE) was calculated as follows:

$$\text{WUE} = \frac{Y}{ET} \times 0.1 \qquad (2)$$

where WUE is measured in kg/m^3, Y is grain yield (kg/ha), ET is evapotranspiration (mm) across the wheat-growing season. The ET was calculated by using the soil water balance equation for the entire growing season as follows:

$$ET = I + P - \Delta S - R - D \qquad (3)$$

where I is irrigation amount (mm); P is precipitation (mm); ΔS is the change of soil water storage—the difference between soil water content values at the planting and end of the harvesting time; R is the surface runoff (mm), assumed to be zero as irrigation water was protected by earth dikes; and D is the downward flux below the crop root zone (mm), assumed to be negligible, since water was applied only to replace soil moisture in the root zone.

2.6 Statistical analysis

The experimental results were subjected to an analysis of variance (ANOVA) for each experimental year, and statistically significant differences among treatments were determined by the F-test. Differences among means for treatments were compared by the Duncan's multiple test，which was applied by using the SPSS statistical software (SPSS 10.0). A probability level of 0.05 (5%) was selected for determining. Winter wheat yield responses to the evapotranspiration were evaluated by regression.

3. Results and discussion

3.1. Total number of irrigation and water received

The total number of irrigation events, comprising water received and consumed during the three growing seasons, (2007-2009) is shown in Table 3 for each treatment. The irrigation amount in 2007 was greater than that in 2008 and 2009; the irrigation amount in 2008 was the least of the entire study period of 2007-2009 due to the higher precipitation in 2008, amounting to 165 mm; this was higher than the average 60-150 mm (Zhang et al., 2003) range. However, the ET of winter wheat during 2007-2009 appeared to vary slightly for the same treatment. For B1 and B2 or D1and D2 treatments, due to the designated sufficient irrigation schedules (no deficit status occurred for soil water-content conditions), the irrigation amount exceeded B3 and B4 or D3 and D4 treatments markedly. In the three growing seasons, treatment B1 received the highest amount of irrigation water and had the highest evapotranspiration

(ET); treatments D3 and D4 received the least irrigation water and had the least ET. Drip irrigation treatments had more number of irrigation due to their small irrigation norm and high irrigation frequency as compared with level-basin irrigation treatments.

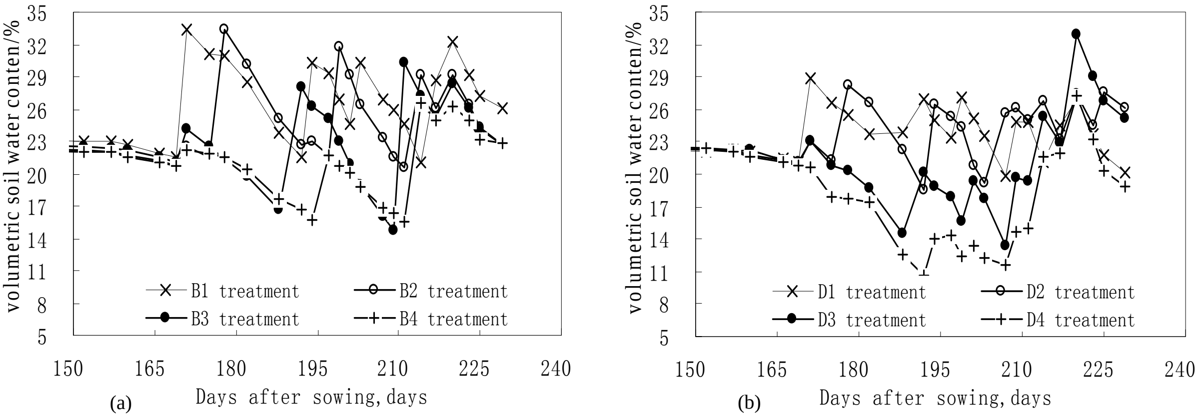
Table 3. Total number of irrigation, water received and consumed during 2006-2009 growing seasons

Treatment	I (mm)	Number of irrigation	P (mm)	ΔS (mm)	R (mm)	D (mm)	ET(mm)
2007							
B1	369	5	110	12	0	0	467
B2	362	4	110	16	0	0	456
B3	249	3	110	18	0	0	341
B4	249	3	110	19	0	0	340
D1	308	7	110	11	0	0	407
D2	305	6	110	19	0	0	396
D3	229	5	110	21	0	0	318
D4	231	5	110	22	0	0	319
2008							
B1	281	4	165	24	0	0	422
B2	282	3	165	22	0	0	425
B3	215	3	165	17	0	0	363
B4	212	3	165	19	0	0	358
D1	249	5	165	13	0	0	401
D2	231	5	165	18	0	0	378
D3	181	4	165	22	0	0	324
D4	189	4	165	21	0	0	333
2009							
B1	333	5	125	24	0	0	434
B2	321	4	125	21	0	0	425
B3	245	3	125	19	0	0	351
B4	226	3	125	21	0	0	330
D1	291	7	125	16	0	0	400
D2	265	5	125	17	0	0	373
D3	234	6	125	23	0	0	336
D4	224	5	125	25	0	0	324

Note: Total number of irrigation and irrigation amounts for all treatments consisted of pre-sowing irrigation and experiment-designed supplemental irrigation during the growth stage of winter wheat.

3.2 Soil water-content variation trend

The soil water-content variation trend under different irrigation treatments were revealed by monitoring soil water content at 0-80 cm of soil depth range through the reviving to maturity phase of winter wheat for each treatment in 2007; this was because the soil water-content variation trend was similar in 2008 and 2009 under the same experimental design. From Fig.1a-b, for the same irrigation method, level-basin irrigation or the drip irrigation method, during most of the growth period, the average soil water content for B1 and B2, or D1 and D2 treatments was higher than that for B3 and B4, or D3 and D4 treatments. Because of the difference of irrigation schedules for different treatments that appeared mainly in the reviving to booting phase, the fluctuation of 0-80 cm average soil water content during the growth period for B3 and B4, or D3 and D4 treatments was more acute than in the B1 and B2, or D1 and D2 treatments. The higher irrigation lower and upper limits, i.e. minimum soil water stress was designed for B1, B2, and, therefore, the irrigation numbers or irrigation frequency was higher than in B3 and B4 treatments (details showed in table 3); the findings were similar for drip irrigation treatments; thus, we can conclude that the higher frequency irrigation treatments contributes to stable soil water condition during the growth stage of winter wheat.



(a) (b)

Figure 1. Measured average volumetric soil water content variation (0-80 cm) trend during the 2007 growing season of winter wheat for different treatments: (a)level basin irrigation(BI) treatments;(b)drip irrigation (DI) treatments.

To further analyze soil water-content variation trend under different irrigation treatments, 0-80 cm of average soil water content for treatments, which had the same irrigation initiating and terminating arrangements but different irrigation methods, were compared in 2007. From Fig.2a-d, it is apparent that, under the same irrigation initiating and terminating arrangements, during most of the growth period, the 0-80 cm average soil water content for level-basin irrigation treatments, including B1, B2, B3 and B4, were higher than that for D1, D2, D3 and D4 treatments; however, higher soil water content was not consistently favorable for crop growth, as certain research results revealed that appropriate water deficit during certain growth stages are helpful to increase yield and WUE (Asseng et al., 1998; Plant et al., 1998).

From Fig.2a-d, fluctuation of 0-80 cm average of soil water content during the growth period for B1, B2, B3 and B4 treatments was more acute than for D1, D2, D3 and D4 treatments. The main reason for this phenomenon was that drip irrigation treatments had more number of irrigation or higher frequency of irrigation compared with level-basin irrigation treatments on the basis of the same irrigation initiating and terminating arrangements. Thus, we concluded that drip irrigation could contribute to stable soil water condition during the growth stage of winter wheat as compared with level-basin irrigation under the same irrigation initiating and terminating arrangements.

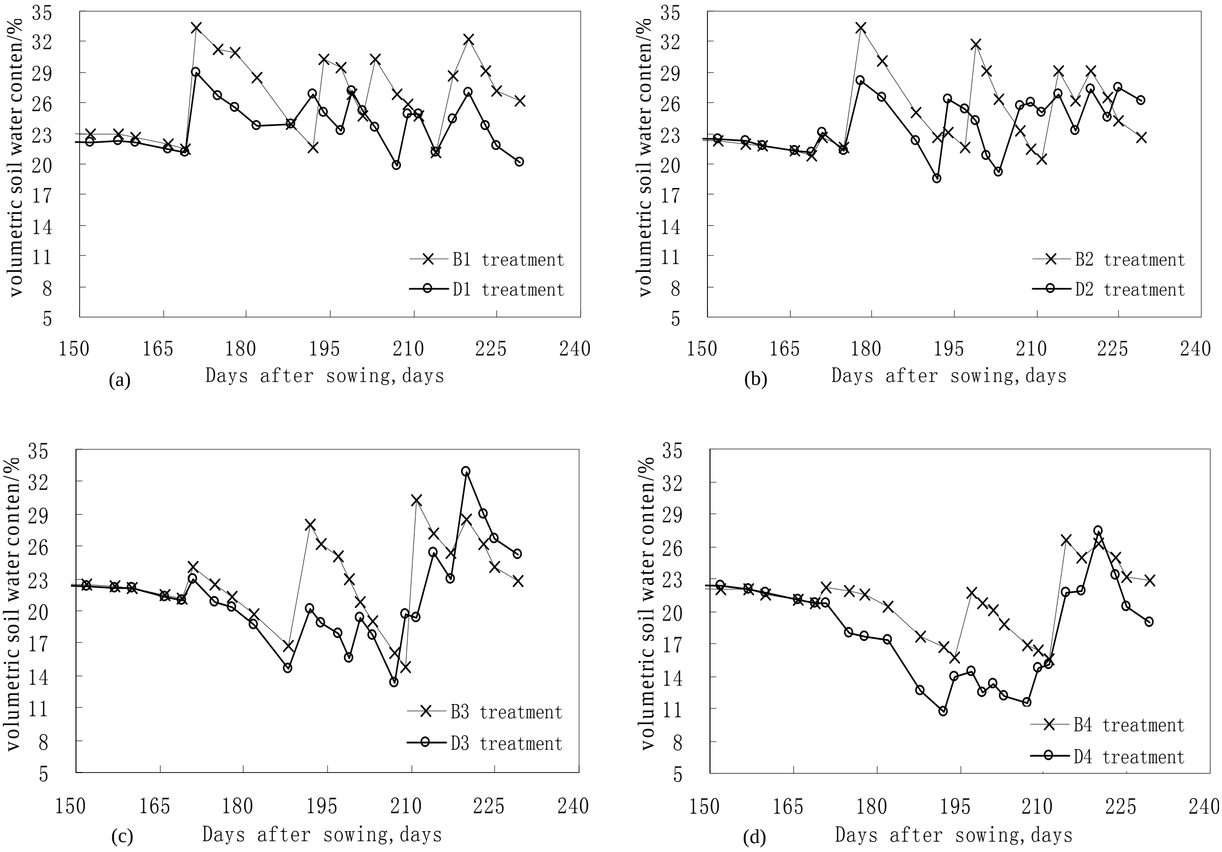


Figure 2. Comparison of average volumetric soil water content variation (0-80 cm) trend during the 2007 growing season of winter wheat for different treatments:(a) B1 and D1; (b) B2 and D2;(c) B3 and D3;(d) B4 and D4.

3.3 Plant growth

3.3.1 Plant height

Data on plant height were recorded on days after sowing (DAS) 172, 182 DAS, 194 DAS, 214 DAS, and 228 DAS, and the date when plant height was observed was scheduled on the same date during 2007-2009. The average plant height data for three years under different treatments were computed and are presented in table 4. As shown in table 4, we note that for any treatment, plant heights were increased with crop growth and reached a maximum value at the heading to milking phase (214 DAS to 228 DAS); plant heights changed minimally at the final stage because irrigation did not affect stem elongation any longer. For level-basin irrigation treatments, the average plant heights for sufficient irrigation treatments, including B1 and B2 treatments, were significantly greater than deficit irrigation treatments, including B3 and B4, at all points of observation ($P_{0.05}$ level). However, from the booting to maturity phase, there were no differences in irrigation schedule for all BI treatments, and water deficits or least supply of irrigation water during the reviving to booting phase affected stem elongation badly for B3 and B4 treatments. The same phenomenon occurred for drip irrigation treatments at other time points of observation, although, at the first observing date (172 DAS) for plant heights, there were no statistically significant differences among drip irrigation treatments. In other words, plant height increased significantly with increase in irrigation levels under the same irrigation method ($P_{0.05}$ level). Thus, we can conclud that the total irrigation amount or irrigation schedules had significant effects on plant heights ($P_{0.05}$ level).

The average plant heights for treatments that had the same irrigation initiating and terminating arrangements were compared, i.e. B1 and D1, B2 and D2, B3 and D3, B4 and D4. From table 4, for the sufficient irrigation treatments, including B1, B2, D1 and D2, there were statistically significant differences ($P_{0.05}$ level) between the two irrigation methods in terms of plant heights; overall, plant heights in B1 and B2 were significantly greater than for D1 and D2 treatments ($P_{0.05}$ level). However, for the deficit irrigation treatments including B3, B4, D3 and D4, plant heights for D3 and D4 were greater than B3 and B4, especially at the heading to milking phase; the plant height difference was statistically significant ($P_{0.05}$ level), and, overall, the drip irrigation method had the advantage of improving plant height as compared with level-basin irrigation method under deficit irrigation with the same irrigation initiating and terminating arrangements.

Table 4. The average plant height of three years(2007-2009) for winter wheat at different observing date

treatment	average plant height of winter wheat(cm)				
	172 DAS	182 DAS	194 DAS	214 DAS	228 DAS
B1	26.82a	46.92a	76.71a	90.11a	89.91a
B2	26.22a	47.09a	76.22a	88.12a	88.17a
B3	23.55b	36.46d	57.97d	75.29c	76.23d
B4	23.35bc	36.82d	55.43d	71.05d	72.02e
D1	23.83b	44.83b	71.17b	88.03a	88.26a
D2	23.76b	41.57c	67.40c	83.72b	84.35b
D3	23.26bc	37.52d	56.48d	75.93c	79.21c
D4	23.60b	36.98d	57.05d	75.97c	77.80cd

NS: The date for observing plant height of winter wheat was scheduled the same during 2007-2009, and letters indicate statistical significance at $P_{0.05}$ level within the same column according to Duncan's multiple range test, and column means followed by the same letter are not significantly different at the $P_{0.05}$ level.

3.3.2 Plant leaf area index (LAI)

Data on the leaf area index (LAI) of winter wheat were recorded by following the procedure designed by Duchemin (2006) along with the process of measuring the plant heights, and the average LAI for three years (2007-2009) under different treatments were computed and are presented in table 5. It is obvious that, for any treatment, the LAI increased with crop growth and reached a maximum value in the jointing to booting phase (194 DAS); thereafter LAI decreased with crop growth approaching the heading to maturity phase. For level-basin irrigation treatments, the average LAI for sufficient irrigation treatments, including B1 and B2 treatments, were significantly greater than deficit irrigation treatments, including B3 and B4, at all observation dates ($P_{0.05}$ level); however, in the booting to maturity phase, there were no differences in the irrigation schedule for all BI treatments, and water deficit or least irrigation water during reviving to booting phases had affected the leaf area expansion adversely for B3 and B4 treatments. This could affect the final crop yield, as leaf area is of great importance for light interception and photosynthesis (Ple´net and Pellerin, 2000). Therefore, greater LAI implies higher crop yields to a certain extent. The same phenomenon also occurred for drip irrigation treatments at all observation dates. For a certain irrigation method, the total irrigation amount or irrigation schedule had significant effects on the LAI ($P_{0.05}$ level).

The average LAI for treatments, which had the same irrigation initiating and terminating arrangements but different irrigation methods, were compared, i.e. B1 and D1, B2 and D2, B3 and D3, B4 and D4. From table 5, we note that, for sufficient irrigation treatments including B1, B2, D1 and D2, there were no statistically significant differences ($P_{0.05}$ level) between the two irrigation methods in terms of LAI on most of the observation dates for B1 and D1, or B2 and D2. The maximum value of LAI between the compared sufficient irrigation treatments, i.e. B1 and D1, B2 and D2, were 8.25 for D1 and 7.70 for D2 and occurred in the jointing to booting phase (194 DAS). For deficit irrigation treatments including B3, B4, D3 and D4, we observe that the LAI of D3 was significantly greater than B3 ($P_{0.05}$ level), and the LAI of the plants of D4 was greater than B4 throughout the growing period; however, there were no statistically significant differences ($P_{0.05}$ level) between B4 and D4 on any of the observation dates. The maximum value of LAI between the compared deficit irrigation treatments, i.e. B3 and D3, and B4 and D4, were 5.27 for D3 and 4.69 for D4 and occurred in the jointing to booting phase (194 DAS). Overall, the drip irrigation method had an advantage of improving LAI as compared with the level-basin irrigation method under deficit irrigation with the same irrigation initiating and terminating arrangements.

Table 5. The average plant LAI of three years(2007-2009) for winter wheat at different observing date

treatment	average plant LAI of winter wheat(cm)				
	172 DAS	182 DAS	194 DAS	214 DAS	228 DAS
B1	3.02a	5.20a	8.17a	5.09a	4.84a
B2	2.99a	4.87ab	7.39b	5.11a	4.18b
B3	2.15c	3.03c	4.34d	4.07c	3.01c
B4	2.17c	2.85d	4.57cd	3.58d	2.47d
D1	2.36bc	5.16a	8.25a	5.19a	4.48ab
D2	2.92a	4.79b	7.70ab	4.56b	4.06b
D3	2.46b	3.56c	5.27c	4.87b	3.44c
D4	2.22c	2.95d	4.69cd	3.68d	2.48d

NS: The date for observing plant leaf area index of winter wheat was scheduled the same during 2007-2009, and letters indicate statistical significance at $P_{0.05}$ level within the same column according to Duncan's multiple range test, and column means followed by the same letter are not significantly different at the $P_{0.05}$ level.

3.4. Grain yield and water-use efficiency (WUE)

The seasonal evapotranspiration (ET), grain yield and water-use efficiency (WUE) for 2007-2009 three growing seasons of winter wheat under different irrigation methods and irrigation schedules are listed in tables 6-9. For level-basin irrigation (BI), as shown in Table 6, yields varied for each year and with treatment, and the average yields (kg/ha) of three growing seasons were 7290, 7200, 5677 and 5240 for B1, B2, B3 and B4, respectively. The maximum yield was achieved in B2 for 2007, and the minimum yield was from B4 for 2009. There were statistically significant differences ($P_{0.05}$ level) among BI treatments in terms of yield at any experimental year or the average yields of three growing seasons. Thus, it could be concluded that total irrigation amount or irrigation schedules had significant influences on winter wheat yields ($P_{0.05}$ level).

Water-use efficiency (WUE) also varied among years and treatments. The mean WUE (kg/m^3) were 1.65, 1.66, 1.61 and 1.53 for B1, B2, B3 and B4, respectively. The maximum WUE was achieved in B2 for 2007, and the minimum WUE was from B4 for 2009. There were statistically significant differences ($P_{0.05}$ level) among BI treatments in terms of WUE at any experimental year or the mean WUE for three growing seasons. The mean WUE for B3 had no significant differences ($P_{0.05}$ level) with the B1 and B2 treatments, although the mean seasonal ET and yield of B3 were smaller than B1 and B2 treatments ($P_{0.05}$ level) during 2007-2009.

Table 6. Grain yield and water-use efficiency (WUE) for level-basin irrigation treatments in 2007-2009

Treatment	ET (mm)			mean	Yield (kg/ha)			mean	WUE(kg/m^3)			mean
	2007	2008	2009		2007	2008	2009		2007	2008	2009	
B1	467a	422a	434a	441a	7850a	7030a	7000a	7290a	1.68a	1.66a	1.61b	1.65a
B2	456a	425a	425a	435a	7900a	6980a	6720a	7200a	1.73a	1.64a	1.58b	1.66a
B3	341b	363b	351b	352b	5780b	5690b	5560b	5677b	1.69a	1.57b	1.58b	1.61ab
B4	340b	358b	330b	343b	5350c	5390b	4980b	5240b	1.57b	1.51c	1.51c	1.53b

NS: Letters indicate statistical significance at $P_{0.05}$ level within the same column in the same growing season according to Duncan's multiple range test; column means followed by the same letter are not significantly different at the $P_{0.05}$ level.

Similar trends occurred for drip irrigation (DI) treatments, as shown in table 7, and yields and WUE also varied by year and treatments; the average yields (kg/ha) of three growing seasons were 6940, 6740, 6310 and 5670 for D1, D2, D3 and D4, respectively. The maximum yield was achieved in D1 for 2007, and the minimum yield was from D4 for 2007; the maximum WUE was achieved in D3 for 2008, and the minimum WUE was from D1 for 2008. For the DI method, total irrigation amount or irrigation schedules had significant effects on winter wheat yields and WUE ($P_{0.05}$ level), and the average yields of three years for sufficient drip irrigation treatments, including D1 and D2, were significantly greater than the deficit drip irrigation treatments, including D3 and D4. However, in terms of mean WUE for three years, the WUE for D3 was statistically significant ($P_{0.05}$ level) greater than B1 and B2 treatments, and the seasonal evapotranspiration (ET) of D3 during 2007-2009 were statistically significant ($P_{0.05}$ level) less than D1 and D2.

Table 7. Grain yield and water-use efficiency (WUE) for drip irrigation treatments in 2007-2009

Treatment	ET (mm)			mean	Yield (kg/ha)			mean	WUE(kg/m^3)			mean
	2007	2008	2009		2007	2008	2009		2007	2008	2009	
D1	407a	401a	400a	403a	7320a	6730a	6780a	6940a	1.80b	1.68c	1.70c	1.72b
D2	396a	378a	373a	382a	7080a	6590a	6550a	6740a	1.79b	1.74b	1.76b	1.76b
D3	318b	324b	336b	326b	6150b	6350a	6420a	6310b	1.93a	1.96a	1.91a	1.94a
D4	319b	333b	324b	325b	5540c	5641b	5830b	5670c	1.74b	1.69c	1.80b	1.74b

NS: Letters indicate statistical significance at $P_{0.05}$ level within the same column in the same growing season according to Duncan's multiple range test; column means followed by the same letter are not significantly different at the $P_{0.05}$ level.

To further analyze yield and WUE under different irrigation methods, yields and WUE for sufficient irrigation treatments, including B1, B2, D1 and D2, and for deficit irrigation treatments, including B3, B4, D3 and D4, were compared and the results are present in tables 8 and 9, respectively. From table 8, we note that there were no statistically significant differences in terms of average yields for B1, B2, D1 and D2 ($P_{0.05}$ level) during 2007-2009, but there were significant differences in terms of mean WUE and

ET for B1, B2, D1 and D2 ($P_{0.05}$ level), and the mean ET for D1 and D2 were significant lower than B1and B2, as showed in table 3, D1 saved about 45mm or 16% irrigation water meanly during 2007-2009 compared with B1, and D2 saved about 55mm or 21% irrigation water meanly during 2007-2009 compared with B2. The mean WUE of D1 and D2 were significant greater than B1and B2 ($P_{0.05}$ level), and maximum mean WUE were achieved in D2 during 2007-2009.

With regard to deficit irrigation treatments under two irrigation methods, including B3, B4, D3 and D4, as shown in table 9, average yields and mean WUE for the DI method were significantly greater than for the BI method ($P_{0.05}$ level) during 2007-2009, however, there were no statistically significant differences in terms of average ET among B3, B4, D3 and D4 ($P_{0.05}$ level). The maximum yield and WUE were all achieved in D3 treatment, and the minimum yield and WUE were from B4 treatment during 2007-2009. Thus, under the condition of deficit irrigation and no significantly different seasonal ET, due to the higher uniform distribution of irrigation water and lower evaporation from the soil surface for DI, which result in higher water use efficiency, compared with BI, the DI method had significant advantage of improving yield and WUE under deficit irrigation condition in comparison with the BI method ($P_{0.05}$ level).

Table 8. Grain yield and water-use efficiency (WUE) for sufficient irrigation treatments in 2007-2009

Treatment	ET (mm)			mean	Yield (kg/ha)			mean	WUE(kg/m^3)			mean
	2007	2008	2009		2007	2008	2009		2007	2008	2009	
B1	467a	422a	434a	441a	7850a	7030a	7000a	7290a	1.68b	1.66b	1.61c	1.65b
B2	456a	425a	425a	435a	7900a	6980a	6720a	7200a	1.73ab	1.64bc	1.58c	1.66b
D1	407b	401b	400b	403b	7320b	6730b	6780ab	6940a	1.80a	1.68b	1.70b	1.72a
D2	396b	378b	373b	382b	7080b	6590b	6550b	6740a	1.79a	1.74a	1.76a	1.76a

NS: Letters indicate statistical significance at $P_{0.05}$ level within the same column in the same growing season according to Duncan's multiple range test; column means followed by the same letter are not significantly different at the $P_{0.05}$ level.

Table 9. Grain yield and water-use efficiency (WUE) for deficit irrigation treatments in 2007-2009

Treatment	ET (mm)			mean	Yield (kg/ha)			mean	WUE(kg/m^3)			mean
	2007	2008	2009		2007	2008	2009		2007	2008	2009	
B3	341a	363a	351a	352a	5780b	5690b	5560b	5677b	1.69b	1.57c	1.58c	1.61c
B4	340a	358a	330a	343a	5350c	5390b	4980b	5240b	1.57c	1.51c	1.51c	1.53c
D3	318b	324b	336a	326a	6150a	6350a	6420a	6310a	1.93a	1.96a	1.91a	1.94a
D4	319b	333a	324a	325a	5540b	5641b	5830b	5670b	1.74b	1.69b	1.80b	1.74b

NS: Letters indicate statistical significance at $P_{0.05}$ level within the same column in the same growing season according to Duncan's multiple range test; column means followed by the same letter are not significantly different at the $P_{0.05}$ level.

In addition, as showed in table 10, compared with B1, which achieved the maximum yields and consumed the most irrigation water among all the treatments, the D3 saved 35% irrigation water meanly during 2007-2009 with only 13% decrease in yield of winter wheat, and the D3 also attained the maximum WUE among all the treatments.

Table 10. Average irrigation water saved and grain yield decrease percentage for treatments compared with B1

Treatment	B2	B3	B4	D1	D2	D3	D4
Irrigation water saved (%)	2	28	30	14	19	35	35
grain yield decrease (%)	1	22	28	5	8	13	22

NS: B1 achieved the maximum average yields 7290kg/ha at consuming the most irrigation water 328mm among all the treatments during 2007-2009

In conclusion, for the two water-saving irrigation methods, irrigation schedules had significant effects on winter wheat yield and WUE. The yields and WUE under sufficient irrigation were significantly greater than in the deficit irrigation treatments ($P_{0.05}$ level). The water deficit or least irrigation water during the reviving to booting phase affected crop growth to some extent, with a resultant marked decrease in final winter wheat yields ($P_{0.05}$ level). For the same irrigation method, all treatments had the same optimal irrigation schedules during the booting to maturity phase. For the BI method, B2 and B3 were recommended for optimal sufficient and deficit irrigation schedule arrangement, respectively, due to their relative small irrigation amount or seasonal ET, high yield and optimal WUE. For DI method, D2 and D3 were recommended for optimal sufficient and deficit irrigation schedule arrangements, respectively.

The BI and DI methods had respective traits and shortcoming, and, thus, had their respective advantages and different application ranges. The water-resource situation has been becoming increasingly serious in the NCP, and it has becomes necessary to adopt water-saving irrigation methods and optimum irrigation schedules for food crop irrigation (Shan et al., 2002; Kang, 2003). Without consideration for the irrigation methods investment, and with a view to attain relative high yield and optimal WUE by consuming water to the least extent possible, the D3 treatment was recommended for winter wheat irrigation in the NCP of the two water-saving irrigation methods and all irrigation schedules. In other words, drip irrigation method and average volumetric soil water content for effective rooting depth range was maintained between 50% FC-75% FC in the reviving to booting phase, 75% FC-FC in the booting to heading phase and 55% FC-70% FC in the milking to maturity phase and, therefore, was regarded as an optimal irrigation model for winter wheat irrigation in the NCP.

3.5 The relationship between yield and evapotranspiration (ET)

Data on evapotranspiration and yields for each treatment during 2007-2009 were collected and processed to establish the functional relationship between yields and evapotranspiration for BI and DI methods, respectively (Fig. 3). In general, from figure 3, we note that, in BI and DI irrigated plants, the yield increased proportionately with the level of seasonal ET in a certain ET variation range, and the relationship between yields and ET could be represented as quadratic functions: $Y(kg/ha) = 1.217x - 0.012x^2 - 23.680$ ($R^2 = 0.51$) and $Y(kg/ha) = 0.426x - 0.004x^2 - 4.144$ ($R^2 = 0.85$).

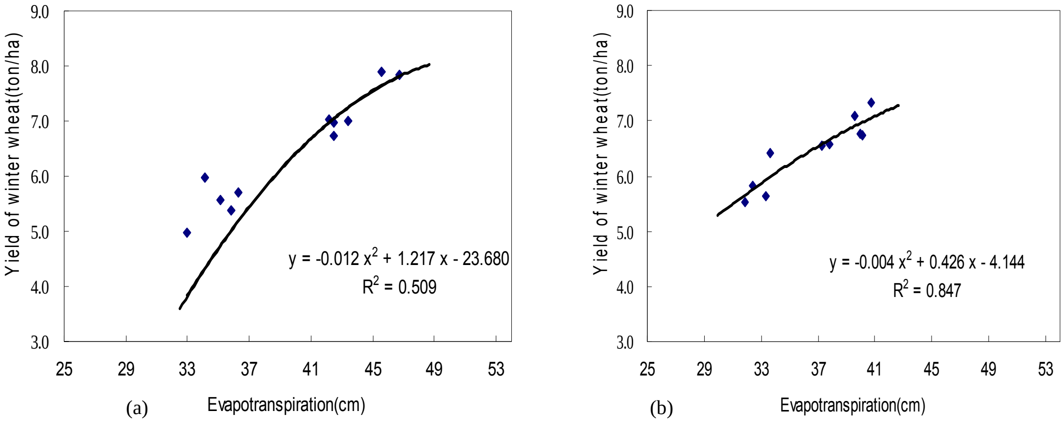


Figure 3. The relationships between evapotranspiration and winter wheat yield in NCP: (a) under level basin irrigation; (b) under drip irrigation.

For the BI and DI methods, respectively. Therefore, the regression analyses indicated that quadratic functions could be used to describe relationships between seasonal ET and grain yield. For the BI method, based on regression functions, grain yield reached a maximum value of 7176 kg/ha at ET of 507 mm; for the DI method, based on the regression functions, grain yield reached a maximum value of 7198kg/ha at ET of 532 mm.

From the above discussion of the BI method, B3 is recommended for optimal deficit irrigation schedule arrangement; for the DI method, D3 is recommended for optimal deficit irrigation schedule arrangement. This is recommended to facilitate attaining of relative high yields and optimal WUE while consuming less water. The irrigation schedules can be designed between 352 mm (average ET for B3) to 507 mm for BI, and between 326 mm (average ET for D3) to 532 mm for DI, to simultaneously achieve relatively high grain yields and WUE. However, an optimal schedule is a relative idea in view of different local irrigation water resources.

From the above results and the realities of irrigation water resources in the NCP, for winter wheat, 352-507 mm of seasonal ET for BI, and 326-532 mm seasonal ET for DI were recommended for choosing the optimal irrigation schedules. Without consideration of irrigation system investment, the D3 treatment or 326 mm of seasonal ET was recommended for optimal deficit irrigation schedule arrangement for a water-conserving effect while also achieving relatively high grain yield and WUE simultaneously.

4. Conclusions

Irrigation is essential to maintain high winter wheat yields and increase its WUE. The water-resource situation has become increasingly serious in the NCP and there is an urgent necessity to develop optimum water managements. Based on field experimental results during 2007-2009 for winter wheat, we concluded that irrigation methods and schedules had significant influences on the variation in trends of soil water content, crop growth and yield of winter wheat, in general.

For any irrigation method, sufficient irrigation treatment or higher irrigation frequency treatments could contribute to stable soil water condition during the growth stage of winter wheat. During the growth period, the fluctuation of soil water content for BI treatments were more acute than in corresponding DI treatments with the same irrigation initiating and terminating arrangements; specifically, the DI method could contributed to stable soil water condition during the growth stage of winter wheat as compared with level-basin irrigation.

For any irrigation method, plant height and LAI increased significantly with increase in irrigation levels ($P_{0.05}$ level), and the total irrigation amount or irrigation schedules had a significant effect on plant height and LAI ($P_{0.05}$ level). For sufficient irrigation treatments as a whole, plant height in B1 and B2 was significantly greater than in the D1 and D2 treatments ($P_{0.05}$ level) at any point of observation; however, there were no statistically significant differences ($P_{0.05}$ level) between the two irrigation methods in terms of LAI during most observations, and the maximum value of LAI was achieved for the DI method in the jointing to booting phase. For deficit irrigation treatments, the DI method had advantage of improving plant height and LAI as compared with the BI method with the same irrigation initiating and terminating arrangements; the maximum value of LAI was also achieved for the DI method in the jointing to booting phase.

Irrigation amount or irrigation schedules had significant effect on winter wheat grain yields ($P_{0.05}$ level) for both irrigation methods, and there were no statistically significant differences in terms of average yields but significant differences in terms of mean WUE for sufficient irrigation treatments under BI and DI methods ($P_{0.05}$ level) during 2007-2009. For deficit irrigation treatments under both irrigation methods, average yields and mean WUE for the DI method were significantly greater than for the BI method ($P_{0.05}$ level) during 2007-2009, although there were no statistically significant differences in terms of average seasonal ET. The DI method had significant advantages of improved yield and WUE under deficit irrigation condition in comparison with the BI method ($P_{0.05}$ level).

From the point of view of attaining relative high yield and optimal WUE by consuming water to the least extent possible, the D3 treatment or326 mm seasonal ET was recommended for winter wheat irrigation in the NCP. Specifically, we ensured that the optimum controlled soil water content at effective rooting depth range in this study for winter wheat irrigation in the NCP would be: 50% FC-75% FC in the reviving to booting growth period, and 75% FC-FC in the booting to heading stage and 55% FC-70% FC in the milking to maturity stage.

Thus, it is possible to maintain relatively high yield and optimal WUE for food crop in the NCP under relatively low water consumption through refining of irrigation schedules and adoption of the appropriate irrigation method. Winter wheat producers and irrigation managers can select a suitable schedule for water management based on the local irrigation water resources, and with special reference to the groundwater resource.

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