Managing Irrigation of Winter Wheat to Maximise Water Use Efficiency and Net Profit in the North China Plain

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Abstract: Winter wheat is one of the staple crops in the North China Plain. High levels of production of this crop largely depend on the use of irrigation. However, irrigation is causing a rapid decline of the groundwater table. To assure sustainable agricultural development in this densely populated region, improvement is needed in farmland water use efficiency (WUE) to reduce the overall application of irrigation water. Irrigation scheduling could reduce the amount of water used to irrigate crops and help to achieve water balance in the North China Plain (NCP). A study at the Chinese Academy of Sciences' Eco-Agro-System Experimental Station in Luancheng in NCP during 1997 to 2000 investigated the effects of different irrigation regimes on grain yield and water use efficiency (WUE) and profits in winter wheat (*Triticum aestivum* L.) The results showed that yield and WUE did not appear to be linearly related to total evapotranspiration. Maximum profit and optimum WUE for winter wheat was obtained using less water than was needed for maximum yield. Based on the sensitivity indices to water stress at various growth stages, optimized irrigation schedule for high yield, efficient use of water and a net profit from winter wheat were established using one, two and three irrigations (60 mm of water per irrigation) in wet, normal and dry years, respectively. Thus, the general practice of irrigating winter wheat four times during the growth period could be changed to irrigation one to three times a year, a practice that would greatly reduce supplemental water use.
Keywords: irrigation scheduling, water use efficiency, net profit, winter wheat, the north China plain

The North China Plain (NCP) is one of the most important grain-production areas in China, especially for winter wheat. Its output accounts for more than 19% of the national wheat production. Due to serious water shortages in NCP, available irrigation is decreasing rapidly. Where groundwater is used, significant amounts have been pumped in recent years, causing serious depletion. At the sites where the experiment was carried out, the water table is declining at a rate of 1 m/yr to 1.5 m/yr. For winter wheat, average rainfall during the growing season from October to May ranges from approximately 60 mm to 200 mm. Supplemental irrigation is required because the water consumption is about 450 mm to 500 mm. Farmers generally irrigate winter wheat three to five times, with 180 mm to 300 mm of the total water application for each season, from wells, rivers or reservoirs.

Despite these serious shortages, wastage of irrigation water is common in NCP because of inefficient methods and poor scheduling, resulting in decreased water use efficiency and profits. The purpose of this research was to determine rational irrigation scheduling for winter wheat with limited availability of water to obtain optimum yields and maximize profits.

The relationships between crop yields and water use are complicated. Yield may depend on when water is applied or on the amount. Information on optimal scheduling of limited amounts of water to maximise yields of high quality crops is essential for efficient use of irrigation water (Al-Kaisi *et al*., 1997). It is a well accepted fact that the various crop development stages possess different sensitivities to moisture stress (Doorenbos and Kassam, 1979; English and Nakamura, 1989; Ghahraman and Sepaskhah, 1997). Timing, duration, as well as the degree of water stress all affect yield.

In this paper, field experiments are described in which winter wheat yields and profits were examined under various irrigation-scheduling regimes. Crop yield/water relations were determined. Water sensitivity indices were analysed at various growth stages. Based on the results, optimum irrigation schedules for maximum net profit for winter wheat were established using a dynamic mathematic model.

1 Materials and methods

1.1 Sites and experiments

Irrigation scheduling experiments were carried out with winter wheat at Luancheng Eco-Agro-System Experimental Station (in a high-production region) from 1997 to 2000. The station is located in the central part of NCP. Soil is loamy soil of high organic content; field capacity of 35.5% and wilting point of 11.3% by volume, for the surface to 100cm soil layer. Rainfall during the experiment is listed in Table 1. Seasonal rainfall is far less than the water requirement of winter wheat calculated by the Penman-Monteith equation recommended by FAO.

Table 1 Rainfall and water requirements (WR) calculated by Penman-Monteith equation during winter wheat growth at Luancheng Station

	1997—1998	1998—1999	1999—2000	Ave. 1975—2000
Rainfall (mm)	127	60.4	54.1	117
WR (mm)	—	—	—	468

The experiments had a randomized design with various combinations of number and timing of irrigations (Table 2), with four replications of each treatment. Surface irrigation was used with plastic tubes, and irrigation water was recorded. Meteorological stations at the experimental sites recorded temperature, rainfall, wind velocity and evaporation from E601 and solar radiation. Plots were 5 m × 8 m, separated by 2 m zone.

Table 2 Number and scheduling of irrigation applied to winter wheat

No. of irrigations	Irrigation scheduling				
	Before over- wintering	Recovering	Jointing	Booting to heading	Milky filling
0					
1			√		
2		√		√	
3	√		√		√
4	√		√	√	√
5	√	√	√	√	√

1.2 Crops and management

Commonly grown varieties were used. Planting is generally in early October with a row spacing of 16 cm and a seeding density of 300/m^2. Harvest is in early June. The straw is returned to the soil. Chemical N, P, and K were applied as base fertilizer, and N was reapplied at the jointing stage. Plots were hand-harvested individually, then a thresher was used to separate the grain.

1.3 Soil-water measurements

Soil-water contents were monitored using a neutron probe (IH-II, UK) at intervals of 7 days for each 20cm layer; aluminium access tubes were installed to a depth of 200 cm for each plot. Evapotranspiration (*ET*) was calculated by the following equation:

$$ET = \Delta S + P + I - D - R \quad (1)$$

where: ΔS = the change of soil-water storage (mm)
P = rainfall (mm)
I = irrigation (mm)
D = drainage from the bottom of root zone (mm)
R = runoff (mm).

Since rainfall intensity is low during winter wheat growth, no runoff occurs and the drainage from the root zone is negligible, in which case *ET* is the sum of rainfall, irrigation and the change of soil-water storage.

2 Results and discussion

2.1 Relation of crop yield and WUE with water consumption

Table 3 shows the three years of results at the two sites. With different combinations of irrigation number and timing, various yields were achieved. The highest yield was not obtained with the most irrigations. A single irrigation produced the highest yield during the 1997—1998 season (relative more rainfall), and four irrigations in 1999—2000 season (least rainfall) produced the highest yield at Luancheng. Much previous work elsewhere has reported that the relationship between yield and water consumption, including irrigation, is not simply linear (Yuan *et al*., 1992). Our results showed that crop yields initially improved with increased water consumption, but beyond a certain water-use level, yields actually decreased (Fig.1): over-irrigation reduced winter-wheat production.

One of the reasons that the grain yield of winter wheat with more frequent irrigation applications was lower than that with less frequent irrigation applications even in very dry years may be that the well-watered treatment tended to have relatively longer growth stages than the ones with less irrigation. Thus, the beginning of milk filling stage of the well-watered treatments would fall behind of the less irrigated treatments. Since, in the piedmont region of Mt. Taihang, dry-hot winds and higher temperatures in late May and June often shorten the milk filling stage of winter wheat and promote maturity. Then the milk filling stage of the well-watered treatment tended to be shortened which reduced seed weight. For example the weight per 1000 seeds of T4 was lower than that of T3 and T2 by 8.6% in 1999—2000 season. Then, the well-watered winter wheat might not produce the maximum yield as the results from this experiment. Thus, moderate deficit irrigation can favor the grain production of winter wheat.

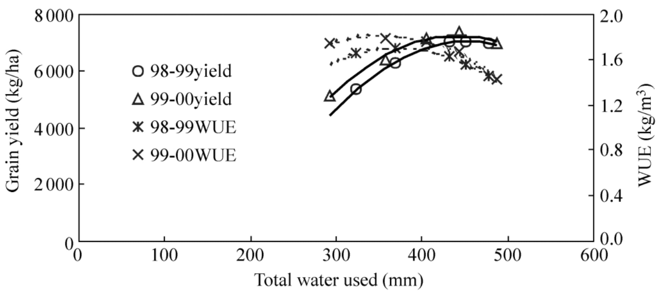

Fig.1 The relation of grain yield and water use efficiency (WUE) with total water used for winter wheat during two seasons (98-99 and 99-00)

Table 3 also shows that with the increase in irrigation (or total water consumption), WUE was decreased markedly. For the purpose of improvement of water use efficiency, there could be an optimum value for irrigation or for total water consumption where yield and WUE were all relative higher. This value would largely depend on the cost of irrigation. With an increase in irrigation cost, more consideration would be placed on the WUE. Then the two irrigation practice in dry years could replace the three irrigation practice for optimum profit.

Table 3 Average grain yield, WUE, components of the total water use of four replicates to each treatments for winter wheat from 1997 to 2000

Seasons	Treatments	Irrigation (I, mm)	Rainfall (R, mm)	Profile depletion (ΔW, mm)	Total water used (TWU, mm)	Grain yield (kg/ha)	WUE (kg/m^3)
1997—1998	T0	0	126.8	172.6	299.4	5413.8a	1.81d
	T1	60	126.8	146.9	333.7	6088.2*b	1.82*d
	T2	120	126.8	111.6	358.4	5954.9b	1.66c
	T3	180	126.8	83.0	389.8	5920.2b	1.52b
	T4	240	126.8	41.0	407.8	5239.8a	1.28a
1998—1999	T0	0	60.4	262.7	323.1	5326.5a	1.65b
	T1	60	60.4	247.8	368.2	6251.0b	1.70*c
	T2	120	60.4	251.3	431.7	7015.8c	1.63b
	T3	180	60.4	211.1	451.5	7021.5*c	1.56ab
	T4	240	60.4	178.1	478.5	6937.5c	1.45a
1999—2000	T0	0	54.1	238.8	292.9	5103.8a	1.74bc
	T1	60	54.1	242.9	357.0	6380.8b	1.79*c
	T2	120	54.1	230.4	404.5	7123.4c	1.76c
	T3	180	54.1	208.5	442.6	7393.2*d	1.67b
	T4	240	54.1	193.6	487.7	6937.8c	1.42a

*: represent the average highest yield or WUE for each season

a-d Means within columns followed by the same letter do not differ significantly at 0.01 level of probability.

2.2 Irrigation water use efficiency

The relation of irrigation to crop yield is called the irrigation-production function. Many researchers (Zhang *et al.*, 1993) have reported that this function can be described with a quadratic relationship:

$$Y=b_0 + b_1W + b_2W^2 \tag{2}$$

where: Y = the crop yield (kg/ha)

W= the total irrigation during the whole crop-growth period (mm)

b_0, b_1 and b_2 are coefficients (kg/ha, kg/(ha • mm), kg/(ha • mm^2), respectively).

Yield increases with irrigation can be divided into three phases. In the first phase the value of the increased yield is in excess of the increase in cost; in the second phase, the value of the increased yield is equal to the increase in cost; and in the third phase, the increase in yield is of less value than the increase in cost. The following equations express these situations.

First phase $\Delta Y\times Py > \Delta W\times Pw$

Second phase $\Delta Y\times Py = \Delta W\times Pw$

Third phase $\Delta Y\times Py < \Delta W\times Pw$

where: ΔY = yield increase from irrigation (kg/ha)

Py = unit price of the crop (yuan/kg)

Pw = unit price of the water (yuan/(ha • mm))

ΔW = the increase in irrigation (mm).

In the first phase, net output value increases with irrigation. In the second phase, the net profit from irrigation is maximum, and, in the third phrase, the net profit from irrigation decreases. Therefore, irrigation quantity for maximum profit is that for the second phase. By derivation of Equation (2) and combination of it with $\Delta Y\times Py = \Delta W\times Pw$, the irrigation amount for maximum profit can be calculated from the following equation.

$$W = (Pw/Py-b_1)/2b_2 \tag{3}$$

Table 4 provides correlations of yield with irrigation for the various seasons. The total irrigation amount for maximum profit was lower than the irrigation amount for maximum yield. Therefore, the general practice of irrigation for maximum yield can be changed in NCP for increased profit savings in large volumes of water. With the worsening water-shortage problem, irrigation costs may increase in the future, then further reductions in usage of water may actually increase profits.

Table 4 Irrigation production function and economic irrigation quota for years at Luancheng (1997—2000) [when calculating irrigation for maximum profit, the price of winter wheat was 1.0 yuan/kg; low water fee 0.1 yuan/m^3 and high water fee 0.5 yuan/m^3 (US$1 = 8.3 yuan)]

Season	Irrigation production function	Irrigation for max. yield (mm)	Irrigation for max. profit (mm)	
			Low fee	High fee
1997–98	$Y = -0.0632W^2 + 12.4\ W + 5418$*	98.3	90.4	58.7
1998–99	$Y = -0.0499\ W^2 + 19.4\ W + 5162$	194	184	144
99-2000	$Y = -0.0489\ W^2 + 23.0\ W + 5075$	235	225	184

**Y* = yield (kg/ha) *W* = total irrigation (mm)

2.3 Optimizing irrigation scheduling for maximum profit

The effect of water stress on the yield of winter wheat depends on the growth stage during which the stress is imposed. The sensitivity indices to water stress (Jensen, 1968) of winter wheat were listed in Table 5 based on the field experiments at Luancheng (Zhang *et al*., 1999). In NCP, rainfall varies greatly during the winter growing season. Taking account of the sensitivity index and rainfall, a dynamic model was used to programme the irrigation schedule for maximum profit. The growth-stage water consumption without water stress is calculated using the Penman-Menteith equation recommended by FAO, based on average meteorological parameters for 1960 to 1990. The crop coefficient is from field experiments (Liu *et al*., 1998). The irrigation scheduling for maximum profit in different rainfall years, dry, normal and wet years are programmed. The type of seasonal rainfall is classified by the meteorological statistical method based on the seasonal rainfall data from 1951 to 1999 in the central part of NCP, with P=75%, 50% and 25% respectively. The quantity of water for each irrigation is assumed to be 60 mm, which is common in the well-pumping irrigation region of NCP.

Table 5 Sensitivity indices (λ_i) of winter wheat to water stress at various growth stages (Luancheng, several years average)

λ_i at growth stage					
Before over-wintering	Recovering	Jointing	Booting	Heading to milky filling	Maturing
0.0781	–0.1098	0.2984	0.2366	0.1102	–0.0541

An asymptotic approximation method was used to program the number of irrigations and their timing. The simulated scheduling with maximum net profits are listed in Table 6 for different seasonal rainfall conditions. The results showed that a single irrigation in wet years, two irrigations in normal years and three in dry years produced maximum profits. The single irrigation would be applied at jointing to booting, at jointing and heading to milky filling for the two irrigations, and before over-wintering, jointing, and heading to milky filling for three. The simulated results were similar to those obtained with the field experiments. And the irrigations were timed when winter wheat is most sensitive to water stress.

Table 6 The simulated irrigation scheduling for maximum profit of winter wheat under different seasonal rainfall regimes (seasonal rainfall was determined using data from 1951 to 1999 for the central part of NCP, and profits were estimated using current prices and costs)

<table>
<tr><th colspan="2" rowspan="2">Seasonal rainfall pattern</th><th colspan="5">Growth stages of winter wheat</th><th rowspan="2">Total (mm)</th><th rowspan="2">Simulated maximum profit (yuan/ha)</th></tr>
<tr><th>Sowing to recovering</th><th>Jointing</th><th>Booting</th><th>Heading to milky filling</th><th>Maturing</th></tr>
<tr><td rowspan="2">Dry</td><td>Average rainfall (mm)</td><td>30.7</td><td>3.5</td><td>6.3</td><td>12.9</td><td>6.4</td><td>59.6</td><td rowspan="2">1,549</td></tr>
<tr><td>Simulated irrigation (mm)</td><td>60</td><td>0</td><td>60</td><td>60</td><td>0</td><td>180</td></tr>
<tr><td rowspan="2">Normal</td><td>Average rainfall (mm)</td><td>52.3</td><td>10.9</td><td>17.4</td><td>16.3</td><td>8.1</td><td>105</td><td rowspan="2">1,609</td></tr>
<tr><td>Simulated irrigation (mm)</td><td>0</td><td>60</td><td>0</td><td>60</td><td>0</td><td>120</td></tr>
<tr><td rowspan="2">Wet</td><td>Average rainfall (mm)</td><td>67.9</td><td>17.4</td><td>22.8</td><td>34.2</td><td>12.1</td><td>154</td><td rowspan="2">1,807</td></tr>
<tr><td>Simulated irrigation (mm)</td><td>0</td><td>0</td><td>60</td><td>0</td><td>0</td><td>60</td></tr>
</table>

3 Conclusions

Crop yields and net profits are important considerations in selecting an irrigation management policy in the water-deficient NCP region of China. Winter wheat, an important crop in NCP, has a high water requirement. Supplemental irrigation is essential. Farmers generally irrigate for maximum yield and, in so doing, sometimes over-irrigate, reducing the yield. With the increasing shortage of water in NCP, irrigation water fees may rise, whereas grain prices may decrease because of current over-production in China. Thus, in choosing an irrigation practice, profit should be the top priority. Based on field experiments, crop-production functions with irrigation water were established. The irrigation water required for maximum profits was found to be less than that needed for the highest yields. A simulation model showed that one irrigation with 60mm water in wet years, two irrigations in normal-rainfall years, and three in dry years produced maximum profits. Based on winter wheat's water-stress sensitivity indices, the irrigations should be timed at jointing to booting for one irrigation, at early jointing and heading to early milky filling for two irrigations, and before over-wintering, jointing to booting and heading to milky filling for three irrigation.

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