

Irrigation Management Using Different Irrigation Scheduling Techniques in Blocked-end Furrows

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Abstract: Surface irrigation under different irrigation techniques is evaluated in this research, based on water applying method, water infiltration depth, and irrigation water use efficiency. For that purpose, field experiments were conducted using cotton grown in silt loam soil at Wuqiao Eco-Agricultural Experimental Station in 2015 season. To evaluate the infiltration and distribution under conventional continuous inflow in comparison to increased discharge and decreased discharge irrigation in blocked-end furrows, nine irrigation treatments were applied. They are known as continuous flow irrigation (CFI), decreased discharge irrigation (DDI) and increased discharge irrigation (IDI). In DDI and IDI irrigation treatments, the inflow should be varied before the completion of the advance phase and cut off time in all treatments when the advance wave reaches the end of the field. The infiltration depth in cm was functioned to opportunity time (τ) in minute for the double ring infiltrometer as: $Z = 0.51\tau^{0.381}$. The average application efficiency of DDI irrigation is higher than that of CFI and IDI irrigation treatments. Decreased discharge in DDI irrigation treatment when the position of the advancing wave front reaches 0.75 of the furrow's length can potentially save water and irrigation time compared with other irrigation treatments.

Introduction

In recent years, several models have been developed for simulating the interactions between the height of the water above the furrow bed and soil water movement, these models are possible to estimate the Infiltration parameters based on different conditions (e.g. border irrigation, blocked-end and free draining furrows) and infiltration equations (e.g. Kostiakov, modified Kostiakov or Saint-Venant equations) [1-10].

Several authors have discussed some irrigation practices to improve irrigation performance. For example, Amer and Amer [11] and Amer [12] discussed some works which conclude that application efficiency can be higher than 86% if furrow irrigation is practiced well under the short irrigation interval using furrow irrigation with little amount of water. Koech, *et al.* [13] developed Real-time prediction of time to cut off (T_{co}) for furrow irrigation to modify and adopt the time to cut-off in order to expected the changes in soil moisture deficit, soil properties and inflow rate whilst the irrigation is still underway. Smith, *et al.* [14] reached that application efficiencies higher than 90% achievable through the use of correct and accurate management of the automated irrigation.

A number of other irrigation management techniques have been developed that can be used to replace the traditional continuous inflow to reduce water losses and improve water uniformity and irrigation water use efficiency during the irrigation event. Some of these methods are as follows: (1) Surge irrigation [15-20], (2) decreased discharge method (Cutback method) is to reduce runoff losses through the commence of the irrigation with a high inflow rate that ensures rapid advance but that reduces the inflow when the water has reached the end of the field [4,21,22]. The advantage of this technique may

be greater since the maximum inflow rate was limited by the recommended erosion limits. Perhaps an inherent limitation of the decreased discharge irrigation is, that it is very sensitive to the field parameters and care is required to ensure that the reduced inflow rate is sufficient to prevent tail end recession, and (3) increased discharge method (inverses cutback) is a technique where the inflow is applied to the furrows until the advance reaches the end of the field. At this point, the flow is increased [23]. The primary advantage of this technique is the reduction in soil erosion from the upper reaches and accurate the advance phase relative to decreased discharge and continuous flow irrigations. Vázquez-Fernández [24] proposed that the inflow should be increased earlier, when the advance has reached ¼ of the field. The increased discharge technique has performed favorably on blocked-end furrows.

Although study conducted in Mexico [23] under bare conditions have indicated that increased discharge irrigation improves irrigation performance comparing with continuous flow irrigation, it is imperative to test its validity under different flow, soil and crop conditions. The objective of this study is to compare between increased discharge, decreased discharge and continuous flow irrigations in block-end furrows for cotton crop in 2015 season to estimate the possibilities of improving furrow irrigation performances. This study proposed that the inflow in the decreased discharge irrigation (DDI) and increased discharge irrigation (IDI) treatments should be varied before the completion of the advance phase and cut off time in all treatments when the advance wave reaches the end of the field. The purpose of such comparison was to confirm the best alternative method to the other.

Materials and methods

Study area

Irrigation evaluations were performed in a cotton field located at Wuqiao Eco-Agricultural Experimental Station, situated to the south of the city of Cangzhou (around 45 km), Hebei Province, China with geographic coordinates: Latitude 37 ° 65' and Longitude 116 ° 37' and an average elevation above sea level to 16 m. The climate is characterized as semi-humid continental, where average annual evaporation range between 1500 – 1800 mm, with summer rains, average annual precipitation is 576 mm and average annual temperature is 12.6 °C.

Soils

The soil of the studied area is silt loam in texture (61.9% silt, 28.3% sand, and 9.8% clay on average), the physical properties of the soil in the study was determined according to [25]. As shown in Table 1. The bulk density increased from 1.44 g/cm³ in the soil surface (0–10cm) to 1.46 g/cm³ in deeply subsurface (20–30cm), but it decreased in the lower depths with an average 1.41 g/cm³ for 0.5 m soil depth.

Table 1. Variation of soil bulk density with soil depth

No	Soil depth (cm)	Bulk density (g/cm ³)
1	0 - 10	1.44
2	10 - 20	1.47
3	20 - 30	1.46
4	30 - 40	1.37
5	40 - 50	1.41
Average		1.43

Inflow rates

Inflows delivered to the furrow were measured at each furrow with flow meters and only one furrow was irrigated at a time and the full inflow through the service point was applied to the that furrow. An averaged initial and later inflow rate were used in all of the evaluations.

Soil moisture

Soil profile moisture was measured throughout the irrigation season with drying a soil to constant weigh. Samples were taken in the centerline of each furrow at 20, 113 and 220 m from the furrow's header. Readings were taken at 0.2 m intervals down the soil profile to a depth of 0.6 m at approximately two to five days before and one to three days after each irrigation. Additional samples were taken between the second and the third irrigation at 20 and 113m of the furrow length.

Experimental treatments

Irrigation furrow treatments were increased and decreased discharge irrigation compared to continuous flow irrigation. Test furrows have the following characteristics: V-shaped, 0.3m top width, 0.2 maximum height, 235 m length, 0.6 m furrow space, and 0.09% slope. The water cut-off in all furrow treatments after the completion of advance phase. The water infiltration depth of soil was obtained with the Kostiakov equation (1932) [26] where the parameters of the Kostiakov equation (1932) were obtained with the double ring infiltrometer. The furrow irrigation system was developed to supply water into cotton field using pipelines thus reducing the wetted surface area in order to save water. Advance and recession times were measured in each evaluated furrow at each 5 m (furrow tail) from the head.

Water uniformity and irrigation water use efficiency

In design and management of irrigation systems, efficient use of water is now often a major goal, as well as production of the crop [27]. Evaluation of furrow irrigation system performance is calculated using the following indicators. Distribution uniformity DU defined as the ratio of the average depth infiltrated in the quarter of the field with the lowest infiltrated depths $\overline{Z_{LQ}}$ to the average infiltrated depth \overline{Z} [27] that is,

$$DU = \frac{\overline{Z_{LQ}}}{\overline{Z}} \quad (1)$$

A second evaluation is also presented with application efficiency (E_a) with no tail water runoff, defined as the ratio of infiltrated water stored in the root zone to the total water applied, application efficiency (E_a) was evaluated considering the methodology proposed by Amer [12]

$$E_a = 1 + \alpha CV \quad (2)$$

$$\alpha = \frac{1}{CV} \left(\frac{d}{\overline{Z}} - 1 \right) \quad (3)$$

$$CV = 0.3 \left(\frac{Z_{\max} - Z_{\min}}{\overline{Z}} \right) \quad (4)$$

In which d= irrigation water depth expressing the plant water requirement; CV = coefficient of variation; α = schedule parameter; Z_{\max} and Z_{\min} = the maximum and minimum infiltration depths.

Results and discussion

Soil infiltration function

Infiltration rates (Fig. 1) was measured using a double-ring infiltrometer. Repeated readings were taken at 2–10 minutes intervals at three different locations. The average points in the figure were taken from the measured values (different locations) at regular time intervals, the difference between duplicate curves at a given time showed at each point. The accurate of the method for estimating infiltration function was excellent considering the average relative error between measurements.

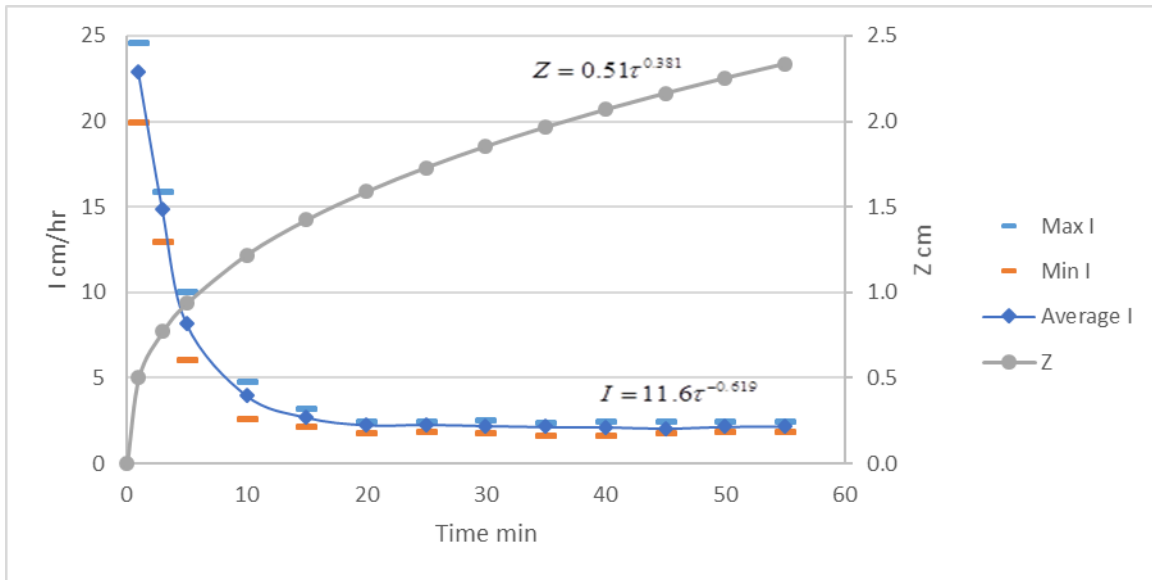


Fig. 1. Field infiltration rate, I (cm/h) and cumulated infiltrated depth Z (cm)

Infiltration rate (I in cm/h) as fitted to Kostiakov equation (1932) [26] was $I = 11.6\tau^{-0.619}$ and the average minimum value of 2.2 cm/h infiltration rate found for the treatments and considered as the basic infiltration rate. Cumulative infiltrated depth Z in cm was integrated from infiltration rate function and reported as $Z = 0.51\tau^{0.381}$, where Z in cm and τ in minute.

Water application by furrow irrigation

Table 2 presents initial inflow rates, later inflow rates, increased/decreased discharge time and fraction of furrow length for which the varied-discharge rate was performed for different irrigations, where CFI, DDI and IDI correspond to continuous flow irrigation, decreased-discharge irrigation and increased-discharge irrigation respectively.

Table 2. Flow Rate, Time, and cumulative volume release of Irrigations

Irrigation Type	Irrigation Event	Initial inflow rate Q_1 (L/s)	Later inflow rate Q_2 (L/s)	L_i^*	$T_{co}=T_a=T_r^*$ (min)	T_i^* (min)
CFI	2	1.14	1.14	-	115.4	-
IDI (1)	1	1.0	2.0	0.90	132.0	115.0
IDI (2)	1	0.9	1.8	0.75	131.0	100.0
IDI (3)	3	0.8	1.6	0.50	116.2	65.0
IDI (4)	3	0.8	1.6	0.25	93.1	25.0
DDI (1)	1	2.0	1.0	0.90	66.0	57.0
DDI (2)	1	1.8	0.9	0.75	78.0	50.0
DDI (3)	3	2.0	1.0	0.50	106.0	26.0
DDI (4)	3	2.0	1.0	0.25	119.00	10.0

* L_i = Fraction of furrow length at the increment/ decrement inflow

T_{co} = Cutoff Time, T_a = Total advance Time, T_r = Irrigation Time

T_i = Time of flow rate increment / decrement

Fig. 2 shows the differences in advance rates resulting from differences in the initial and later inflow rates. The advance phase of the DDI (1) and DDI (2) are very fast compared with other irrigation types, because the initial inflow was high and the later low inflow was performed when the advance phases

reached 0.9 and 0.75 of the furrow length, respectively. Fig. 2 also shows that the combination of initial high flow rate and later low flow rate can decrease the advance time. Therefore, this combination increases the opportunity time in the lower quarter of the field. The advance phase time in all treatments ranged between 66 min and 131 min.

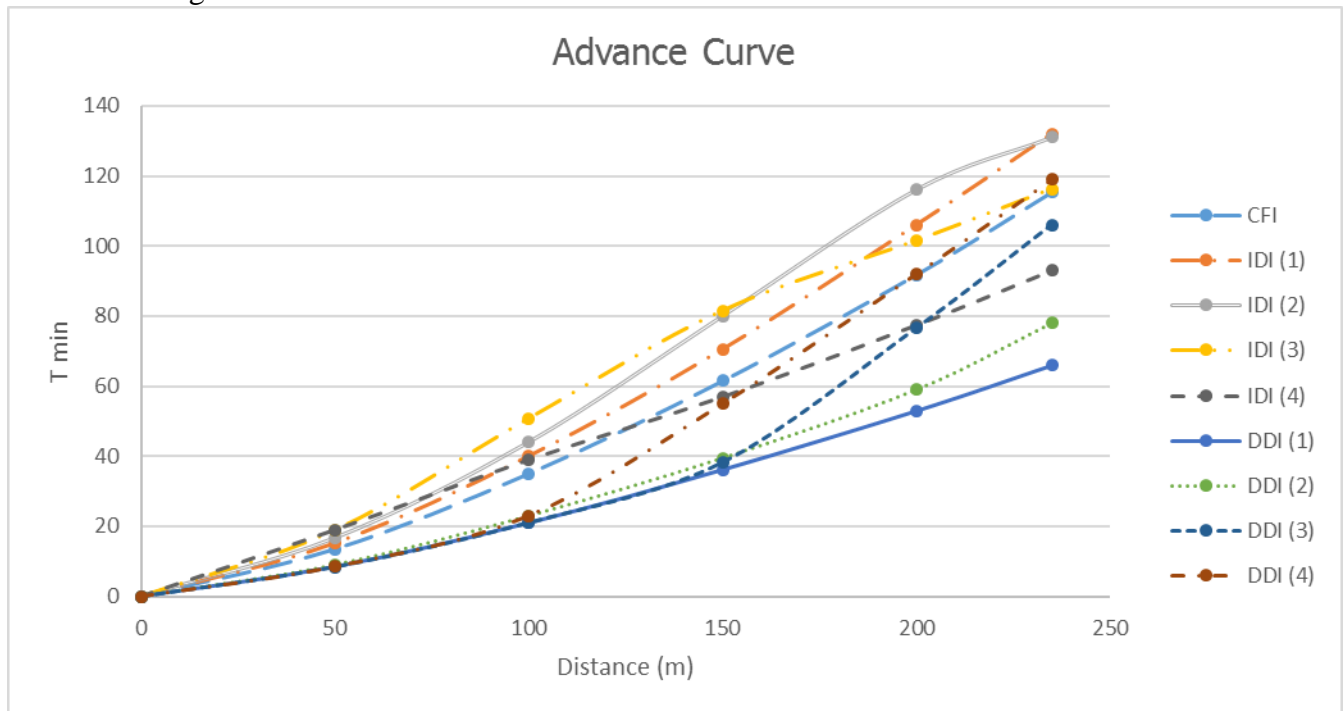


Fig. 2. Water advance trajectories

Table 3 shows the infiltration water depth and the average infiltration depth along the furrow for different irrigation techniques where the cumulative depth of infiltration Z (mm) is calculated by the previous Kostiaikov equation (where the opportunity time is the difference between the measurement advance and recession time). The difference between average infiltration depth and the infiltration depths along the furrows (DU, E_a) described in the following sections.

Table 3. Infiltrated water depths (mm)

Irrigation Type	Distance in the furrow (m)						Average
	0.0	50.0	100.0	150.0	200.0	235.0	
CFI	33.3	33.1	32.6	34.3	34.6	33.9	33.6
IDI (1)	35.2	35.3	38.5	41.2	41.4	40.5	38.7
IDI (2)	35.1	35.1	37.7	39.3	39.7	39.6	37.7
IDI (3)	33.7	33.0	33.5	35.2	36.8	36.7	34.8
IDI (4)	31.3	30.4	32.1	35.7	36.6	36.3	33.7
DD1 (1)	28.0	28.1	29.7	32.8	34.4	34.3	31.2
DD1 (2)	29.1	29.2	28.5	29.3	29.7	28.6	29.1
DD1 (3)	32.3	32.5	32.3	34.4	33.9	32.2	32.9
DD1 (4)	33.5	33.8	36.8	36.8	33.8	32.4	34.5

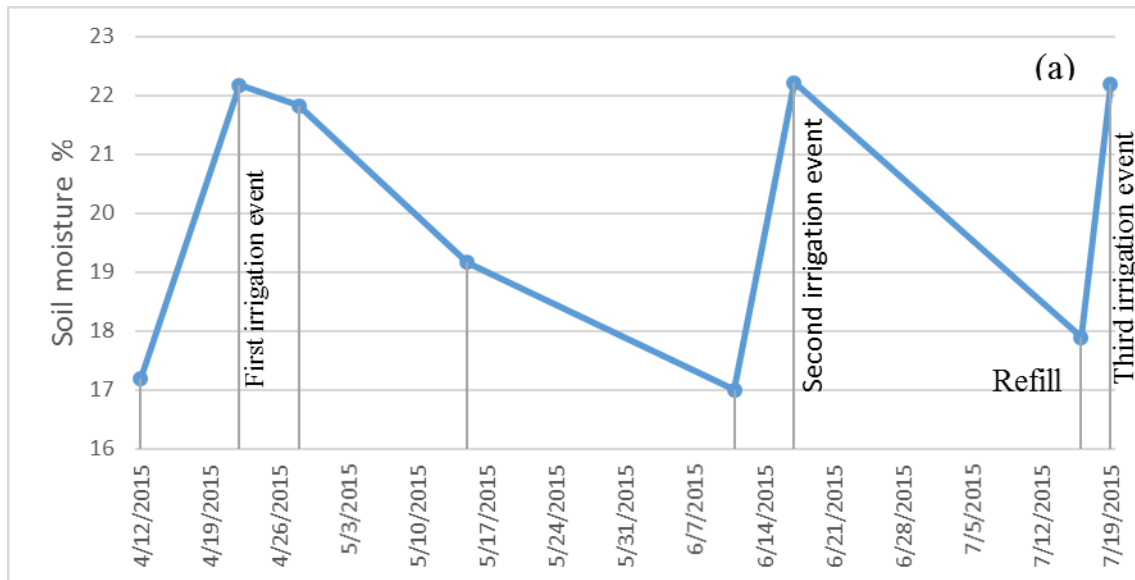


Fig. 3. Soil moisture measurement in time throughout the irrigation season

Consistent irrigations were applied at the experimental field, irrigations commencing at approximately 17% moisture contents (see moisture content plot in Fig.3).

Irrigation performances and scope for improvement

Table 4 presents the results of irrigation efficiencies and field observations for CFI, DDI and IDI irrigation treatments. According to this information, in general the DDI irrigation duration was short compare with CFI and IDI irrigations, The distribution uniformity and application efficiency were estimated for CFI irrigation treatment, the values were 100% and 96.9% respectively, the irrigation time was 115.4 min and the cumulative water release was 7.89 m³. In the IDI irrigation treatments the flow increase was performed when the water reached 0.9, 0.75, 0.5 and 0.25 of the furrow's length, obtained DU = 100% and irrigation application efficiencies obtained averaged 92% (range 90 – 94%) with the highest application efficiency when the inflow increase was performed at 0.5 of the furrow's length. The cumulative water release was the highest in the IDI irrigation treatments. In the DDI irrigation treatments the flow decrease was also performed at 0.9, 0.75, 0.5 and 0.25 of the furrow's length. DU was 97.5% and irrigation application efficiencies averaged 94.7% (range 89 – 97%) with the highest application efficiency and distribution uniformity when the inflow decrease was performed at 0.5 and 0.75 of the furrow's length. DDI irrigation saves water and irrigation time compared with CFI and IDI irrigation treatments. The DDI irrigation strategy inevitably results in water amount rapidly reaches to the low quarter and hence increased infiltration opportunity in the lower quarter and increased therefore application efficiency and distribution uniformity. The DDI (2) irrigation duration was appropriate to the prescribed inflow rates and that conferred high efficiencies, the distribution uniformity (DU) and application efficiency were 98.6% and 97.7%, respectively. There is therefore an evidence to encourage the DDI irrigation method when the water reaches 0.75 of the furrow's length. According to these and previous results, DDI irrigation method is recommended to be used to establish good irrigation practices.

The crop growth stage is the critical factor in determining the initial and the later inflow rate to be used, this meant that the optimum irrigation initial and later inflow varied from one irrigation to the next according to the crop root depth or requirement infiltration depth. The inflow strategy used in this study is where the irrigation is shut off at the end of the field. In this case, selection of the initial and later inflow rate depends entirely on having right strategy and calculating the correct duration for initial and later inflow rates. For example, the DDI (2) irrigation treatment, the initial flow rate was 1.8 l/sec, the later flow rate was 0.9 l/sec, and the $T_{co}=T_r$ is 78 min; hence, a volume of 6.78 m³ of water is applied.

At these specified flow rates, the average infiltration depth was 29.1 mm. Using flow rates higher than those used in DDI (2) irrigation treatment, the average infiltration depth would have been increased from the measured value 29.1 mm and arguably is a suitable strategy when crop is in a mid-season. Consequently, this approach is adaptive. It is also very easy to managed, when the irrigation advance reaches at the end field, the irrigation is shut off. An instruction close the furrow end can be installed to record the rate of advance of the irrigation flow down the furrow and the flow depth. The irrigated area received only surplus of water along the furrow lengths, therefore, the irrigated area did not have any water deficit and storage efficiency was 100% for all treatments.

Table 4. Irrigation system evaluation

Parameters	Furrow Irrigation								
	Tco =Ta								
	Continuous flow	Increased inflow treatments				Decreased inflow treatments			
Treatment	CFI	IDI (1)	IDI (2)	IDI (3)	IDI (4)	DD1 (1)	DD1 (2)	DD1 (3)	DD1 (4)
Cumulative release (m3)	7.89	9.09	8.88	8.16	7.86	7.23	6.78	7.74	7.89
Toff=Ta=Tr (min)	115.4	132	131	116.2	93.1	66	78	106	119
Distribution uniformity (DU) (%)	100	100	100	100	100	100	98.6	97.8	93.9
Coefficient of variation (CV)%	1.84	4.76	3.71	3.29	5.48	6.18	1.23	1.97	3.85
Schedule parameter (α)	-1.70	-1.86	-1.90	-1.60	-1.80	-1.67	-1.65	-1.11	-1.59
Application efficiency (Ea) (%)	96.90	91.10	92.9	94.70	90.1	89.6	97.7	97.8	93.9

Summary and Conclusion

The main goal of this work was to compare water irrigation efficiencies between continuous flow irrigation, decreased discharge irrigation and increased discharge irrigation in blocked-end furrows. For that purpose, field evaluation experiments were carried out in cotton field from the 15th of April 2015 to the 20th of September 2015 season to estimate the possibilities of improving furrow irrigation performances under conditions of north China plain. The field is a silt loam soil, irrigated using dry furrow irrigation with blocked-end 235 m long and 0.09% slope. IDI irrigation and DDI irrigation were applied based on inflow variation regime when the advance has reached 0.9, 0.75, 0.5 and 0.25 of the field length. All treatments were applied based on water cut off when the position of the advancing wave front reaches the lower boundary. The results from the evaluations demonstrated higher efficiencies for the DDI irrigation method than the CFI and IDI irrigation method, because of achieving high efficiencies. It was also found that DDI irrigation method, when the position of the advancing wave front reaches 0.75 of the furrow's length, saved more water and time than the other irrigation treatments. Therefore, a certain amount of water that otherwise would have been lost as deep percolation was saved. That is a convenient management in the periods of short supply of water.

It is recommendable that other evaluations with different characteristics of discharge techniques should be done, such as surge flow or decreased discharge irrigation that reduce the inflow rate when the advance of the slowest advancing furrow reaches the end of the field and inflow is stopped when the requirement efficiency reaches 100%.

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