FIELD EVALUATING SYSTEM PERFORMANCE OF A VARIABLE RATE CENTER PIVOT IRRIGATION SYSTEM

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ABSTRACT

Control unit plays an important role in variable rate irrigation (VRI) system. In this study, a VRI system was retrofitted from one three-span (140 m) conventional center pivot machine. The performance of the constructed VRI system was tested under three typical operating conditions: all sprinklers on, partial sprinklers off, and sprinklers regulated by “on/off” pulsing of the solenoid valves. The results indicated that the target application depth could be achieved accurately through setting a specific rotation speed of the pivot under uniform rate irrigation condition. Under variable rate irrigation condition, the accuracy of application depth obtained through regulating moving speed of variable rate center pivot irrigation system was related to pivot speed and duty cycle of solenoid valves. Overall, the actual application depth was 0.48 mm and 1.46 mm underestimated when variable rate irrigations were achieved by partial sprinklers off and by sprinklers regulated by “on/off” pulsing of the hydraulic valves, respectively. The error of water applied for impulse type variable rate irrigation could be decreased through optimizing the cycle time of solenoid valves.

Keywords: center pivot; variable rate irrigation; application depth

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1. Introduction

Recent advances in communications and microprocessors have enabled the general implementation of site-specific water applications by self-propelled center pivot and lateral move sprinkler irrigation systems (Kranz et al., 2012). Because the information of the accuracy and uniformity of an irrigation system are essential for the success of precision irrigation management, many works has been reported on the evaluation of variable rate irrigation (VRI) system performance (King et al., 2005; Dukes and Perry, 2006; O'Shaughnessy et al., 2013; Zhao et al., 2014; Sui and Fisher, 2015). These researches demonstrate that the overlap of sprinkler coverage between the adjacent control zones could reduce uniformity in each zone. After excluding these data points from the water collectors, the uniformity along the pivot radial direction and in the direction of pivot travel was similar to the value for uniform rate irrigation. Therefore, the size of management zone should not be too small to guarantee the application uniformity. Meanwhile, Sui and Fisher (2015) reported that the difference between the target and applied depth was still existent and increased with the decreasing of target depth through testing a center pivot VRI system consisted of a commercial Valley VRI zone control package.

The system performance of a variable rate center pivot was investigated in the present study. It aims to study the influence of travel speed of center pivot and duty cycle of solenoid valves on applied depth, and to seek the method to reduce the error between the target and applied depth for center pivot VRI irrigation system.

2. Materials and Methods

2.1 System description

The variable rate center pivot irrigation system was developed by China Institute of Water Resources and Hydropower Research. It was retrofitted from a 140 m long center pivot irrigation system with three-spans and an overhang. Variable rate water application along the center pivot lateral was achieved by regulating the duty cycle of the solenoid valves. A duty cycle of zero represents an off mode of the sprinklers. Nelson R3000 rotating sprayers were installed at 4.2 m spacing along the lateral at a height of approximately 1.2 m above ground level. Each sprayer was equipped with a 138 kPa pressure regulator and an electric solenoid valves, and the control units were mounted on the top of the pivot towers to implement variable rate irrigation. The geo recognizers designed with radio frequency identification technology were used for zones control in the direction of pivot travel. Performance status of the system can be remotely monitored using a smart device like smart phone. The modified Heermann and Hein uniformity coefficient (CU_{HH}) and the lower quarter distribution uniformity (DU_{lq}) along the pivot lateral were reduced by 9 and 19 percentiles compared with the uniform rate irrigation (Zhao et al., 2014).

2.2 Experiment setup

To confirm the accuracy of application depth, the system was tested under both uniform rate irrigation and variable rate irrigation conditions. Plastic catch-cans with a 21.5 cm diameter opening and 23.0 cm high were used to measure the depth of application. In the uniform rate irrigation test, the collectors were uniformly spaced with 3 m along two radial legs. The stagger distance of collectors between the two lines was 1.5 m and the angle between the two radial lines of water collectors was 8°. In accordance with the ASABE Standard S436.1 (ASABE Standards, 2007), no collectors were placed within the inner 20% of the effective radius of the pivot. The application depth was the weighted average depth caught by collectors. Under uniform rate irrigation condition, the target depth (h_k, mm) for a specific rotation speed percentage (K) can be computed from the application depth at a full speed of 100% (h, mm). The rotation speed of the pivot is obtained through regulating the percent timer that is defined as the percentage of time that the end tower moves in 1 min.

$$h_k = h / K \quad (1)$$

In the variable rate irrigation test, because there is no established standard for evaluating the performance of VRI systems, the application depth was measured in a manner similar to O'Shaughnessy et al. (2013). To eliminate the influence of the overlap of sprinkler coverage between the adjacent control zones on application depth, 4 rows of water collectors was placed in the middle of the zone with a grid 1×3 m along the direction perpendicular to the direction of the pivot travel. Every row included 5 collectors. The application depth for each zone was the mean depth caught by these 20 collectors. Assuming that the construction of VRI system had minor influence on hydraulic performance of center pivot irrigation system, the target depth for VRI system could be calculated by the product of h_k and duty cycle of solenoid valves.

$$h_{v-k} = mh_k = m \cdot h / K \quad (2)$$

where h_{v-k} is the application depth of VRI system when rotation speed of the pivot is set as K, mm; m is the duty cycle of solenoid valves. The duty cycle is the ratio of "on" time to cycle time (CT) of solenoid valves.

2.3 Test procedures

The pivot was stared at approximately 8° before reaching the first test line to allow the water pressure and application rate of the system to stabilize at the desired testing conditions. The true amount of water caught by the collector was measured immediately after the sprinkler leaving it to prevent the water evaporation in each collector. For the uniform rate irrigation test, the application depth was measured through setting percent timer at 20%, 40%, 60%, 80% and 100% (U1 - U5). For the variable rate irrigation test when partial sprinklers off, three percent timer of 40%, 80% and 100% and four sprayer banks of 3, 4, 5 and 6 were evaluated in the experiments (V1-1 — V1-11). For the variable rate irrigation test when sprinklers regulated by “on/off” pulsing of the solenoid valves, three percent timer of 20%, 30% and 50%, three sprayer banks of 3, 4 and 5, and four duty cycle of solenoid valves of 20%, 50%, 80% and 100% were evaluated (V2-1 — V2-6). The default CT of solenoid valves was 60 s. At the same time, the application depth was tested when CT was set as 50, 35, 30 and 20 s. The first sprinkler bank proximal to the pivot point was ignored during application depth testing since this area presents a small amount of the total system coverage. The application depth for impulse type variable rate irrigation was tested in zone 2. Details of the experimental treatments are presented in Table 1.

Table 1 Experimental treatments for application depth testing of center pivot variable rate irrigation system.

Irrigation type	Treatments	Number of sprayer banks	Percent timer/%	Duty cycle of solenoid valve/%
Uniform rate irrigation	U1	1	20	100
	U2	1	40	100
	U3	1	60	100
	U4	1	80	100
	U5	1	100	100
Variable rate irrigation when partial sprinklers open	V1-1	3 (8，10，16)	100	100，0，100
	V1-2	3 (8，10，16)	100	0，100，0
	V1-3	4 (8，6，15，5)	100	100，0，100，，0
	V1-4	5 (6，7，7，6，8)	100	100，0，100，0，100
	V1-5	5 (6，7，7，6，8)	80	100，0，100，0，100
	V1-6	5 (6，7，7，6，8)	40	100，0，100，0，100
	V1-7	5 (6，7，7，6，8)	100	0，100，0，100，0
	V1-8	5 (6，7，7，6，8)	80	0，100，0，100，0
	V1-9	5 (6，7，7，6，8)	40	0，100，0，100，0
	V1-10	6 (6，6，6，6，6，4)	100	0，100，0，100，0，100
	V1-11	6 (6，6，6，6，6，4)	100	0，100，0，100，0，100
Impulse type variable rate irrigation	V2-1	3 (8，11，15)	30	100，80，50
	V2-2	4 (8，9，6，11)	30	100，20，50，100
	V2-3	4 (8，9，6，11)	30	100，20，100，50
	V2-4	4 (8，9，6，11)	20	100，20，100，50
	V2-5	4 (8，9，6，11)	50	100，20，100，50
	V2-6	5 (8，9，6，6，5)	30	100，20，100，50，80
	CT=50 s	4 (8, 9, 9, 8)	100	0, 20, 50, 80
	CT=50 s	4 (8, 9, 9, 8)	50	0, 20, 50, 80
	CT=35 s	4 (8, 9, 9, 8)	50	0, 20, 50, 80
	CT=30 s	4 (8, 9, 9, 8)	50	0, 20, 50, 80
	CT=20 s	4 (8, 9, 9, 8)	50	0, 20, 50, 80

Note: the serial values in brackets following the numbers of sprayer banks represent the number of sprinklers in each management zone from the pivot to the end of the lateral.

The mean absolute error (MAE) was calculated to compare how close the measured application depths were to the target depth. The mean bias error (MBE) was calculated to determine the precision of application depth:

$$\mathrm{MAE} = \frac{1}{b}\sum_{j=1}^{b}\left|P_j - O_j\right| \qquad (3)$$

$$\mathrm{MBE} = \frac{1}{b}\sum_{j=1}^{b}(P_j - O_j) \qquad (4)$$

where P_j is the target depth at position *j* in the management zone, O_j is the corresponding observed value, and *b* is the number of collectors used in the zone.

3. Results and Discussion

3.1 Application depth for uniform rate irrigation

Under the uniform rate irrigation condition, the 100% rate of center pivot rotating produced an application depth of 6.1 mm. A significant linear equation was observed between target application depths calculated by Eq. 1 and the measured application depths at a significant level of $p < 0.001$ with a determination coefficient (R^2) of 0.997. The coefficient of fitted linear equation (0.972) was very close to 1. This suggested that the target application depth could be achieved accurately through setting a specific rotation speed of the pivot when the speed was varied between 20% and 100% of the full speed under uniform rate irrigation condition.

3.2 Application depth for variable rate irrigation

The mean absolute error (MAE) and the mean bias error (MBE) of application depth in each management zone for variable rate irrigation when partial sprinklers open and impulse type variable rate irrigation are shown in Tables 2 and 3, respectively. Under the condition of variable rate irrigation when partial sprinklers open, the MAE ranged from 0.32 to 0.56 mm when the pivot rotating speed was 100% of the full speed, and the number of sprayer banks had minor influence on it. Both MAE and MBE indicated an increasing trend with the decreasing of pivot rotating speed. The mean MBE of the eleven treatments was -0.48 mm, demonstrating the application depth was 0.48 mm underestimated. Under the condition of impulse type variable rate irrigation, the mean MAE (1.57 mm) and absolute value of MBE (1.46 mm) was larger than the values for variable rate irrigation when partial sprinklers open. Averagely, its application depth was 1.46 mm underestimated. This demonstrated that the combination of impulse type on-off of solenoid valves and go-stop running mode of pivot increased the error of target application depth for impulse type variable rate irrigation.

Table 2 Mean absolute error (MAE) and mean bias error (MBE) of water application depth in different management zones when partial sprinklers open.

Error	Management zone	V1-1	V1-2	V1-3	V1-4	V1-5	V1-6	V1-7	V1-8	V1-9	V1-10	V1-11	Average value
	2		0.42					0.54	0.59	1.45	0.38		
	3	0.41		0.56	0.41	0.5	2.61					0.56	
	4							0.41	0.69	1.23	0.41		
	5				0.32	0.56	1.51					*	
MAE (mm)	6										*		0.75
	2		-0.19					-0.24	-0.53	-0.88	0		
	3	-0.02		-0.39	-0.13	-0.18	-2.61					-0.39	
	4							-0.04	-0.30	-1.14	-0.09		
	5				0.09	-0.16	-1.47					*	
MBE (mm)	6										*		-0.48

Note: * indicates missing values.

Table 3 Mean absolute error (MAE) and mean bias error (MBE) of water application depth for impulse type variable rate irrigation.

Error	Management zone	V2-1	V2-2	V2-3	V2-4	V2-5	V2-6	Average value
MAE (mm)	2	2.89	0.88	0.55	1.85	2.45	0.83	1.57
MBE (mm)	2	-2.89	-0.86	-0.48	-1.85	-2.45	-0.21	-1.46

Table 4 Mean absolute error (MAE) and mean bias error (MBE) of water application depth for impulse type variable rate irrigation with different cycle time of solenoid valves.

CT（s）	Percent timer（%）	MAE (mm)	MBE (mm)
50	100	0.37	-0.19
50	50	1.56	-1.56
35	50	1.59	-1.59
30	50	0.95	-0.92
20	50	2.24	-2.24

To decrease the error between the measured and target application depth for impulse type variable rate irrigation, the mean absolute error (MAE) and the mean bias error (MBE) of application depth for impulse type variable rate irrigation with different CT of solenoid valves are shown in Table 4. The minimum MAE and absolute value of MBE were obtained when CT was set as 50 s at a full speed of 100%, being consistent with the results when CT of solenoid valves was 60 s (Table 2). Given a specific value of percent timer of 50%, the MAE was basically equal to the absolute values of MBE, and the MAE for the cycle time of 50 s (1.56 mm) was similar to the value when cycle time was 35 s (1.59 mm). The maximum and minimum values of MAE and absolute values of MBE were found in the treatments with CT = 20 s and CT = 30 s, respectively. This suggested that an optimum cycle time might exist to minimize the error of application depth for impulse type variable rate irrigation.

4. Conclusions

After constructing the variable rate center pivot irrigation system, its application depth was tested under three typical operating conditions: all sprinklers on, partial sprinklers off, and sprinklers regulated by “on/off” pulsing of the solenoid valves. Under uniform rate irrigation condition, the target application depth could be achieved accurately through setting a specific rotation speed of the pivot. When partial sprinklers off, the application depth was 0.48 mm underestimated, and its error was negatively correlated to the pivot rotation speed. When sprinklers regulated by “on/off” pulsing of the solenoid valves, the application depth was 1.46 mm underestimated, and its error could be decreased through optimizing the cycle time of solenoid valves.

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