WATER FLOW RATES FROM A SITE-SPECIFIC IRRIGATION SYSTEM

K. C. Stone, E. J. Sadler, J. A. Millen, D. E. Evans, C. R. Camp

ABSTRACT. *Site-specific irrigation is defined as delivering different prescribed depths of water to specific areas in irrigated fields. Since the 1990s, site-specific irrigation research has been expanded to include the delivery of water and nutrients to specific field areas based on soil type, soil moisture status, crop needs, and other user-defined objectives. A site-specific center pivot irrigation system was designed and installed in a field with highly variable soils of the U.S. eastern coastal plain. The system consisted of 13 segments along the 140-m length of the three-tower center pivot with three delivery manifolds in each segment. The system was designed to apply approximately 12.5 mm of water in any selected segment when operated at 50% travel velocity. Quantifying water application depth and uniformity from the site-specific irrigation system is essential to documenting the system's performance and interpreting experimental results. We developed a measurement system to evaluate the water delivery rates of the irrigation system. We compared the measured water delivery from each segment of the site-specific irrigation system to the design parameters. We found that the irrigation system was delivering water to the control areas at rates approximately as it was designed. A total of 77 segment and manifold combinations were tested. Of these 77 combinations, we found that 7 had flow rates greater than 10% different from the design flows. The manifolds with the lower flow rates typically were more likely to differ significantly from their design values. This was most likely related to potential clogging of the low flow nozzles that have smaller orifices. When the manifolds were used in combination, they compensated for each other and produced application depths near the design depths.*

Keywords. *Site-specific agriculture, Irrigation, Site-specific irrigation, Center pivot.*

Site-specific, or variable-rate, irrigation research has been conducted since the early to mid-1990s. This research has focused on the delivery of prescribed quantities of water to specific locations or areas within a field. The reasoning for spatial water application was based on spatial variability in topography, soil type, soil water availability, landscape features, cropping systems, and more recently for water conservation. For example, in the Pacific Northwest, water application to rocked outcrops is discouraged. Likewise, applications to adjacent roads and water bodies not only produce potentially liable situations, but also wastes energy and could degrade the water bodies. In areas with rolling terrain, water applications upslope can produce runoff and result in ponding at lower elevations under the same irrigation system. In the southeastern Coastal Plain, the soils often exhibit greater variability within comparable field sizes than do soils in other regions. Additionally, the soils in this region are usually coarse-textured sandy soils with low water-holding capacities, and in many areas these soils will have compacted layers restricting root growth to shallow depths (Camp et al., 1998). The combination of highly variable soils with low water holding capacity along with highly variable rainfall creates a complex management scheme to optimize production and water usage. From over 11 years of spatial observations of crop growth, especially during periods of plant water stress, it was determined that water relations were the major factor contributing to yield variability for soils in the southeastern Coastal Plain (Karlen et al., 1990; Sadler et al., 1995a, 1995b, 2000a, 2000b). To address these concerns about water relations on the highly variable soils, a site-specific center pivot irrigation machine was developed in 1995 at the ARS Coastal Plains Soil, Water, and Plant Research Center (Florence, S.C.).

The system consisted of a modified commercial three-tower 140-m center pivot irrigation system with additional manifolds and control devices to apply water on approximately 100-m^2 control areas. The control areas were 9.1 × 9.1 m. Additional details on the system design and construction are included in the methods. The site-specific irrigation system has been used on various crops including corn, soybean, and wheat. Details on the cropping systems and results for spatial water applications were presented by Camp and Sadler (2002).

The site-specific irrigation system has been in operation since 1995. At its initial installation and during the design of the system, preliminary measurements of nozzle wetting pattern and manifold wetting patterns were made (Omary et al., 1997). The system uses industrial spray nozzles to reduce overspray from the small control areas. The spray nozzles

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The authors are **Kenneth C. Stone, ASABE Member Engineer,** Agricultural Engineer, USDA-ARS, Coastal Plains Soil, Water, and Plant Research Center, Florence, South Carolina; **E. John Sadler, ASABE Member,** Research Leader, Soil Scientist, USDA-ARS, Cropping Systems and Water Quality Research Unit, University of Missouri, Columbia, Missouri; **Joseph A. Millen, ASABE Member,** Agricultural Engineer, **Dean E. Evans,** Agricultural Engineer, and **Carl R. Camp, ASABE Member Engineer,** Agricultural Engineer, USDA-ARS, Coastal Plains Soil, Water, and Plant Research Center, Florence, South Carolina. **Corresponding author:** Kenneth C. Stone, USDA-ARS, 2611 West Lucas St., Florence, SC 29501; phone: 843-669-5203; fax: 843-669-6970; e-mail: stone@florence.ars.usda.gov.

have graduated orifice sizes to achieve very low flows at the inner pivot segments and much higher flow rates at the outer pivot segments, which are needed to achieve the same application depth throughout. Camp et al. (1998) measured the water depth distribution along the radius and tangentially for one 10-m segment to determine the appropriate control zone within the segment. Since this initial testing, no further testing of the water distribution along the pivot has been performed. Since the precise application of water is essential to interpreting the cropping data from the site-specific irrigation system, it is imperative that a thorough and detailed analysis of the water flow rates from the system be performed. We conducted this test to determine if the actual applications were within design specifications. Additionally, verification of design water flow rates would be valuable if other researchers proposed development of a similar system.

The objectives of this article were 1) to exhaustively test the water delivery system from the site-specific irrigation system segments and 2) to determine the potential impact of system water delivery on previously interpreted data.

Methods

A center pivot system was modified to perform variable rate water applications to 9.1- × 9.1-m areas (Omary et al., 1997; Camp et al., 1998). The center pivot was divided into 13 segments, each 9.1 m in length (fig. 1). These segments create rings as the pivot turns a full circle. Three pressure-regulated manifolds were installed in each segment, each with six nozzles sized (table 1) to deliver 1x, 2x, or 4x of a base application depth at that location along the center pivot length (referred to as flow rate). Combinations of the three manifolds provided variable depths of 0 through 7x of the base rate. The 7x depth was 12.7 mm when the outer tower was run at 50% of full speed. For field experiments, a computer and programmable logic controller (PLC) (model 90-30, GE Fanuc, Charlottesville, Va.) controlled the manifolds on the center pivot based on user inputs via a computer program and interface to the pivot controller. A more detailed description of the water delivery system may be found in Omary et al. (1997) and of the control system in Camp et al. (1998).

Test Equipment

Water was diverted from the manifolds into a collection gutter for each manifold (two gutters for the 4x manifold) using lay flat tubing (fig. 2). Two gutters were required for the 4x manifold to provide enough capacity to handle the flow rates created by the outer pivot segments. The four gutters were used to convey the water through flexible down spouts into 132-L horizontal tanks. The tanks were suspended from load cells to weigh the incoming water. The 1x manifold had a 90-kg capacity load cell (Model SB0-200, Transducer Techniques Inc., Temecula, Calif.), and the 2x and 4x had 136-kg load cells (Model SB0-300).

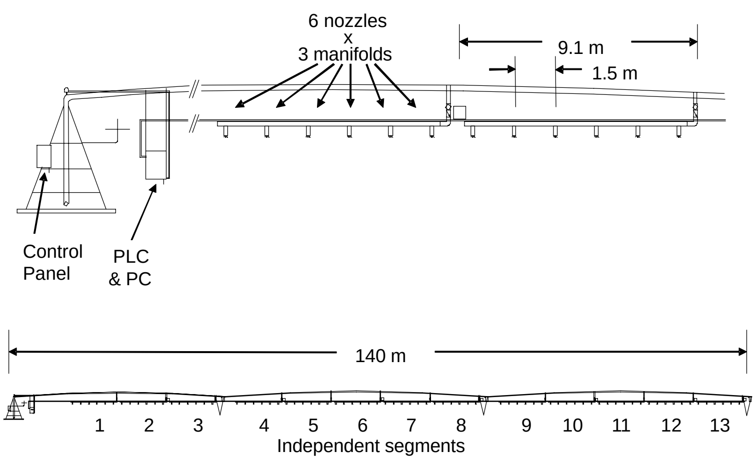

Figure 1. Schematic diagram of modified center pivot irrigation system (Camp et al., 1998).

Table 1. Design flow rates for the site-specific center pivot irrigation systems (Full Cone − Industrial Spray Nozzles, Spraying Systems Co., Wheaton, Ill.).

	Manifold Number Nozzle Size (Mfg Designation)			Design Pressure (kPa)			Design Flow Rate/Manifold (L/min)		
Segment	1x	2x	4x	1x	2x	4x	1x	2x	4x
3	1/8G2.8W	1/8G5.6W	1/4HH12W	103.4	103.4	103.4	7.50	15.22	31.80
4	1/8G4.3W	1/8G8W	1/4HH14W	68.9	103.4	137.9	9.77	21.80	43.15
5	1/8G5.6W	1/4G10W	3/8HH17W	68.9	103.4	137.9	12.72	27.25	52.24
6	1/8G5.6W	1/4HH12W	3/8HH20W	103.4	103.4	137.9	15.22	31.80	61.32
7	1/8G8W	1/4HH12W	3/8HH24W	68.9	103.4	103.4	18.17	31.80	65.87
8	1/8G8W	1/4HH14W	3/8HH27W	68.9	103.4	103.4	18.17	38.61	72.68
9	1/8G8W	1/4HH14W	1/2HH30W	103.4	137.9	103.4	21.80	43.15	81.76
10	1/4G10W	3/8HH17W	1/2HH35W	68.9	103.4	103.4	22.71	45.42	95.39
11	1/4G10W	3/8HH17W	1/2HH45W	103.4	137.9	68.9	27.25	52.24	102.21
12	1/4G10W	3/8HH20W	1/2HH40W	103.4	103.4	103.4	27.25	54.51	109.02
13	1/4G12W	3/8HH27W	1/2HH45W	103.4	68.9	103.4	31.80	61.32	122.65

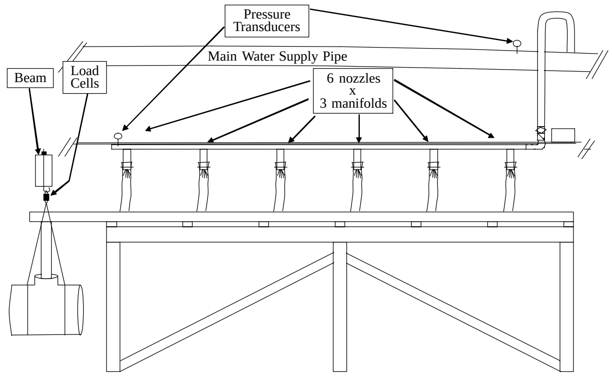

Figure 2. Schematic diagram of the uniformity testing apparatus.

Pressure was measured at the end of each manifold and in the pivot lateral using 0- to 340-kPa (0- to 50-psig) pressure transducers (Model #206, Setra, Boxborough, Mass.). Water temperature was read using a 24-ga type T thermocouple wire (OMEGA Engineering, Inc., Stamford, Conn.).

All readings (pressure, temperature, weight, and time) were taken on a 1-s interval using a data logger (CR23X , Campbell Scientific, Inc., Logan, Utah). To facilitate testing of the system, the solenoids for each of the three manifolds were rewired to allow control from a four-toggle switch box. The first switch started data collection and supplied power from the Campbell data logger to the other three switches (one for each of the three manifolds). These three switches controlled relays on the individual manifold solenoids.

Test Procedure

Segments 1 and 2 were not used for experiments; therefore, tests were started on segment 3 and were performed radially outward to segment 13. Data for each segment were collected by running the manifolds in order from 1x to 7x and repeating for a total of three replications. Approximate run times were determined before the test by calculating time for a full tank based on the pivot design specifications.

Data Analysis

After the tests were concluded, the data were imported into SAS (SAS Institute, Inc., Cary, N.C.) for analysis. Typical data output can be seen in figure 3 with preceding and ending curvilinear portions with a straight line section in between. The straight line portion of the test was used to determine application rates at steady rate conditions after pressure had equalized and valves were fully opened.

The steady rate condition was determined using an algorithm to find where the slope of volume versus time became constant. The slope at a given time increment was calculated using the 15 data points (1-s interval) before and after the time in question. When the difference between calculated slopes was less than 0.09 kg/s (because of the noise in the load cells, we chose a small value as our minimum detectible difference), the start of the steady rate flow portion of the test was identified. The end of the run was determined from the switch closure by the Campbell datalogger when the solenoids were switched off.

The slopes of the linear steady-rate sections were calculated with linear regression using the SAS Proc Reg.

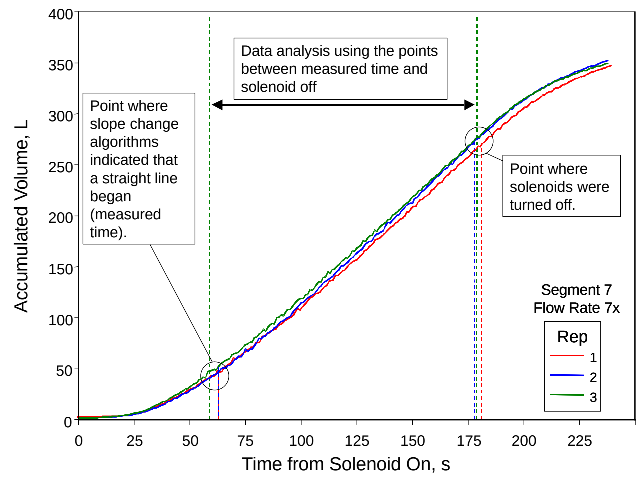

Figure 3. Example flow test data and procedure for determining flow rates.

The SAS system was also used to calculate data means and to calculate t-test results for the flow and pressure data.

Additionally, we calculated the application depths using the speed (1.92 m/min at the outer tower) assumed for 50% travel by the design documents. The speed at a given segment was determined by the ratio of distance from the center of the pivot to the center of the segment in question divided by the distance from the pivot center to the outer tower. The application volume was then divided by the application area covered to calculate the application depth.

Results

The water flow rates from the site-specific irrigation system were overall very similar to the design criteria (table 2) for most segment/flow rate combinations. The differences between design and measured flows show that 7 of the 77 total tested segment/flow rate combinations had measured flows that were greater than 10% different from the design flows (table 3). For a more rigorous comparison, 28 of the 77 total tested segment/flow rate combinations had measured flows greater than 5% different from the design flows. These differences ranged from 24% under application for segment 3/1x flow rate to 19% over application at segment 6/4x flow rate.

We considered two potential causes of the deviations from design flow rate, orifice clogging, and pressure variations from design. The under application at the inner segments appeared to be caused by partial clogging of the small 1x nozzles. This can occur over time with accumulation of deposits in the water delivery system. Field observations and experience with the irrigation system recognized this as a potential problem for the inner segments with the low flow rate manifolds. Additionally, the flow rates from the nozzles can be influenced by the operating pressures from the individual manifolds. Table 4 shows that the pressures for the manifolds were mostly within 10% of design pressures. Most of the manifolds with higher pressure differences, located on the 4x manifold and on the outer segments, did not appear to have an influence on the flow rates.

Table 2. Measured flow rates from the control segments and water rate application depths.

	Flow Rate (L/min)													
	Flow Rate													
	1x		2x		3x		4x		5x		6x		7x	
Segment	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std	Mean	Std
3	5.69	0.18	15.71	0.21	21.40	0.80	33.54	0.34	40.63	0.91	49.98	0.14	56.88	0.89
4	9.18	0.13	20.92	0.42	30.60	0.07	44.06	0.80	53.05	0.43	64.86	0.33	74.27	0.45
5	12.70	0.06	25.43	0.42	38.65	0.78	61.70	3.66	75.48	1.11	88.08	0.74	101.00	0.36
6	15.33	0.38	33.18	0.55	50.17	2.45	72.80	0.97	87.24	3.06	101.30	2.37	118.10	3.69
7	14.42	0.50	35.09	0.32	51.60	0.69	62.01	1.09	80.21	0.86	101.10	3.66	116.80	2.73
8	16.62	0.05	37.31	0.73	54.93	0.91	77.70	2.46	90.91	0.99	104.20	13.04	128.50	1.15
9	20.29	1.05	46.62	3.84	66.11	1.53	79.89	2.80	100.70	0.70	120.80	2.75	141.30	4.11
10	21.00	0.69	48.64	2.13	69.33	0.89	98.59	2.13	119.20	5.11	145.90	6.53	175.00	5.40
11	26.66	0.42	51.46	2.08	79.33	2.03	98.09	0.71	128.80	3.13	147.50	1.24	175.80	0.62
12	26.77	0.55	57.59	1.63	84.28	5.83	108.40	1.57	133.30	4.04	163.00	4.41	189.90	5.50
13	33.22	0.22	62.95	0.63	95.16	0.39	121.90	1.01	155.70	3.16	186.90	3.54	220.00	5.41

Table 3. Percentage differences between design and measured flow rates.

	% Difference between Design and Measured Flow Volume						
	Fow Rate						
	1x	2x	3x	4x	5x	6x	7x
Segment	Mean	Mean	Mean	Mean	Mean	Mean	Mean
3	0.24	−0.03	0.06	−0.05	−0.03	−0.06	−0.04
4	0.06	0.04	0.03	−0.02	0.00	0.00	0.01
5	0.00	0.07	0.03	−0.18	−0.16	−0.11	−0.10
6	−0.01	−0.04	−0.07	−0.19	−0.14	−0.09	−0.09
7	0.21	−0.10	−0.03	0.06	0.05	−0.04	−0.01
8	0.09	0.03	0.03	−0.07	0.00	0.06	0.01
9	0.07	−0.08	−0.02	0.02	0.03	0.03	0.04
10	0.08	−0.07	−0.02	−0.03	−0.01	−0.04	−0.07
11	0.02	0.01	0.00	0.04	0.01	0.04	0.03
12	0.02	−0.06	−0.03	0.01	0.02	0.00	0.00
13	−0.04	−0.03	−0.02	0.01	−0.01	−0.02	−0.02

SINGLE MANIFOLD TESTS

For most of the manifolds, the measured flow was similar to the design values. To determine if the measured flows were significantly different from the design values, we subtracted the measured flow from the design flow. A positive value then indicated an under water application and a negative value indicated an over application of water. Theses differences were then compared to zero using a t-test. For the 1x manifold, we found six segments were significantly different ($P \leq 0.05$) from the design values (table 5). Most of the 1x manifolds under applied water. This corresponded to field operational experience in which we found more plugging with the 1x manifold particularly with the lower flows on the inner pivot segments. For the 2x manifold, we found five segments were significantly different from the design flows. The segments closer to the pivot point with lower rates accounted for most of the segments with significant differences. For the 4x manifold, 5 of the 11 tested segments were significantly difference from design flows. Four of the five segments significantly different than design flow rates were in the inner portion of the pivot with only segment 11 significantly different for the outer segments. These results indicate that using the lower flow rate nozzles would require frequent monitoring and maintenance to keep them operating efficiently.

MULTIPLE MANIFOLD TESTS

Using manifolds in combinations to obtain the other flow combinations for the pivot (3x, 5x-7x) had similar results with most significantly different flows in the inner portion of the pivot. The combination of using more than one manifold often produced a compensating effect on the additive flows. This compensating effect occurred when one manifold over-applied and another manifold under-applied. The compensating effect was more pronounced in the higher-flow outer segments (8-13) with only 9 of the 24 segment/flow combinations having significant differences from the

Table 4. Manifold pressures, standard deviations, and percentage differences between design and measured manifold pressures.

	Manifold Pressure (kPa)								
	Flow Rate								
	1x			2x			4x		
Segment	Mean	Std	% Diff	Mean	Std	% Diff	Mean	Std	% Diff
3	104.3	2.82	−0.01	102.70	2.98	0.01	99.60	4.22	0.04
4	64.99	2.55	0.06	106.20	4.01	−0.03	142.00	6.56	−0.03
5	65.68	2.67	0.05	106.60	4.23	−0.03	145.40	1.96	−0.05
6	95.88	5.21	0.07	103.30	4.95	0.01	145.80	9.69	−0.06
7	62.74	1.58	0.09	98.98	2.72	0.04	92.89	6.79	0.10
8	63.78	1.17	0.08	96.63	3.90	0.07	98.19	5.18	0.05
9	99.84	3.18	0.03	148.10	13.32	−0.07	96.48	3.49	0.06
10	63.47	3.42	0.08	99.56	9.61	0.04	91.05	10.81	0.12
11	98.40	1.70	0.05	135.40	15.80	0.01	60.08	0.89	0.13
12	100.70	1.71	0.03	97.01	10.29	0.05	95.69	6.55	0.08
13	98.94	2.10	0.04	66.53	1.28	0.04	90.89	2.13	0.12

Table 5. T−test parameters for the testing of the flow rates from the site−specific pivot.

	Probability of Sample Not Equal to Zero													
	Flow Rate													
	1x		2x		3x		4x		5x		6x		7x	
Segment	t	Prob.	t	Prob.	t	Prob.	t	Prob.	t	Prob.	t	Prob.	t	Prob.
3	17.32	<0.01	−4.15	0.05	2.84	0.10	−8.81	0.01	−2.08	0.29	−35.59	<0.01	−4.63	0.04
4	8.05	0.02	3.62	0.07	23.33	<0.01	−1.96	0.19	−0.52	0.66	0.52	0.65	1.75	0.22
5	0.59	0.61	7.48	0.02	2.92	0.10	−4.48	0.05	−16.41	<0.01	−19.97	<0.01	−42.08	<0.01
6	−0.52	0.65	−4.31	0.05	−2.23	0.16	−20.44	<0.01	−6.06	0.03	−5.99	0.03	−4.58	0.04
7	12.92	<0.01	−17.57	<0.01	−4.73	0.02	6.11	0.03	6.26	0.10	−1.65	0.24	−0.62	0.60
8	59.11	<0.01	3.06	0.09	3.53	0.07	−3.53	0.07	−0.10	0.93	0.94	0.45	1.47	0.28
9	2.51	0.13	−1.57	0.26	−1.30	0.32	1.16	0.37	7.11	0.02	2.61	0.12	2.28	0.15
10	4.32	0.05	−2.62	0.12	−2.33	0.14	−2.60	0.12	−0.35	0.76	−1.36	0.31	−3.68	0.07
11	2.45	0.13	0.65	0.58	0.14	0.90	10.03	<0.01	0.37	0.74	9.67	0.01	16.32	<0.01
12	1.52	0.27	−3.28	0.08	−0.75	0.53	0.69	0.56	1.30	0.32	0.20	0.86	0.27	0.81
13	−11.00	<0.01	−4.50	0.05	−8.99	0.01	1.37	0.31	−0.70	0.55	−1.45	0.28	−1.37	0.31

design values. For the inner segments (3-7), 10 of the 20 segment/flow rates were significantly different from the design values.

Application Depths

The water flows measured during the flow test were integrated with the data from the individual segments to calculate the water application depths under each pivot segment (figs. 4-7). The target water application depth of the pivot was to apply 12.45 mm when the pivot was traveling at 50% of full speed. The individual manifolds would deliver 1.78, 3.56, and 7.11 mm for the 1x, 2x, and 4x manifolds, respectively. The 1x manifold application depths (fig. 4) show that most of the nozzles used for the pivot applied less water than the design depth of 1.78 mm. The actual application depths measured were within approximately 0.25 mm from the design depths and were mostly below the nozzle specification depths. The 2x manifold application depths (fig. 5) for both the nozzle design depths and measured application depths were also within approximately 0.25 mm the design application depths. The 4x application depths (fig. 6) were within 0.5 mm for all but two of the pivot segments. Those 4x manifolds for the two segments were earlier identified as applying more water than they were originally designed to apply. These two manifolds had pressures that were within 6% of the designed pressures. The combination of all three manifolds for the 7x flow (fig. 7) shows that their combined application rates were within approximately 0.5 mm of the design application depth for the pivot. Again, the manifolds for segments 5 and 6 were about 2 mm higher than the design value. These data indicate that the pivot was performing fairly close to design tolerances.

Based on the data presented on the flow distribution collected from the site-specific irrigation system, the impact of water application on the previously reported results would be very minimal. The previous research was conducted on

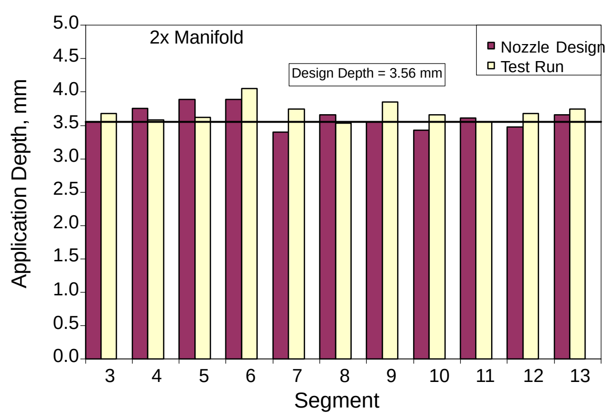

Figure 5. Water application depths for the 2x manifold for each pivot segment.

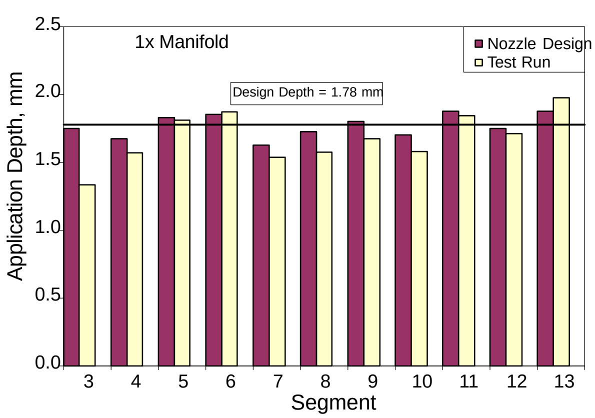

Figure 4. Water application depths for the 1x manifold for each pivot segment.

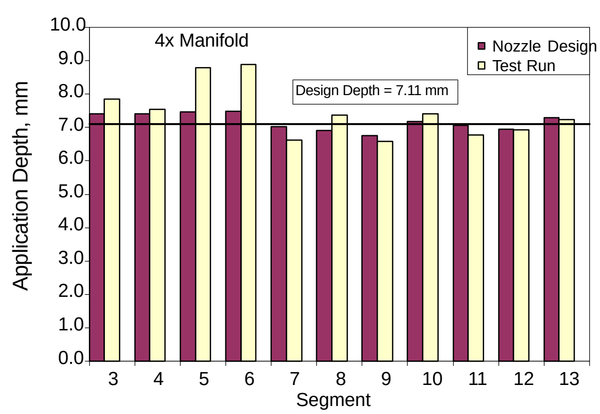

Figure 6. Water application depths for the 4x manifold for each pivot segment.

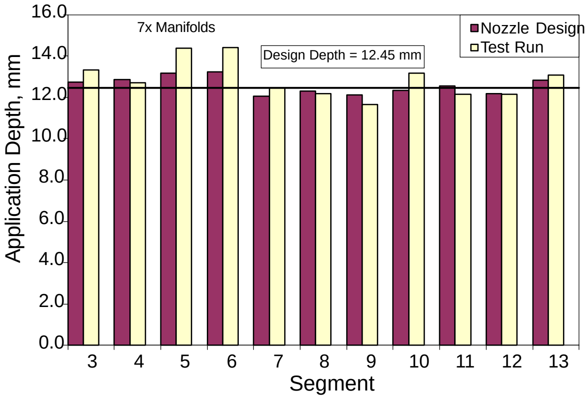

Figure 7. Water application depths for the 7x manifold for each pivot segment.

segments 8-13 due to on-the-ground plot layouts. The results shown in figure 7 indicate that the application depths were very similar to the design depths and nozzle specifications.

Conclusion

The site-specific center pivot irrigation system was evaluated to quantify its water delivery characteristics. The system was designed to apply approximately 12.5 mm of water when operated at 50% travel velocity. We found that of the 77 tested combinations of manifolds and pivot segments, 7 had flow rates greater than 10% different from the design flow rates. The 1x manifold had 6 of 11 tested segments significantly different from designed flows using a t-test. The 2x and 4x manifolds each had 5 of 11 tested segments significantly different from design flows. When the manifolds were used in combinations, they compensated for each other to apply water more closely to the designed application rates and depths. These results indicate that system maintenance and frequent monitoring are essential to precise water delivery. The results from this study suggest minimal impacts on the previously interpreted data.

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