CENTER-PIVOT IRRIGATION SYSTEM FOR INDEPENDENT SITE-SPECIFIC MANAGEMENT OF WATER AND CHEMICAL APPLICATION

B. A. King, R. W. Wall, T. F. Karsky

ABSTRACT. *The development of lateral-move and center-pivot irrigation systems equipped for spatially variable water application and those equipped with an independent chemical application system have largely evolved independently. Integration of independent site-specific water and chemical application with lateral-move and center-pivot irrigation systems has received little attention. Increasing the utility of site-specific management technologies added to automated irrigation systems will increase their cost effectiveness and commercial potential. An independent chemical application system capable of variable rate application was installed and tested on a 4-span center-pivot irrigation system equipped for variable rate water application. The chemical application system was assembled using mini-sprinklers and common commercial irrigation system components. For uniform chemical application, the coefficient of uniformity (CU) values ranged from 84 to 90 providing acceptable application uniformity. For variable rate chemical application, CU values ranged from 79 to 93 and measured mean area-weighted relative application values were well correlated with target relative application values with* R^2 *of 0.9 or higher. Field testing of the chemical application system demonstrated that it can be used to effectively apply spatially variable chemical application concurrent and independent of spatially variable water application.*

Keywords. *Irrigation, Center-pivot, Site-specific, Chemigation, Application uniformity.*

Conventional water and nutrient management assumes uniform fields and uniform application, neither of which are true in practice. Spatially variable water management may be needed because of field spatial variability in infiltration, drainage, and runoff of irrigation and precipitation. Crop vigor can vary due to spatially variable nutrient and/or water availability, salinity, pest intensity and plant density, all of which can result in spatially variable crop evapotranspiration and nutrient uptake. The existence of spatially variable water and nutrient requirements under conventional uniform management means that optimum water and chemical application on the field scale is not achievable, resulting in less than maximum water and nutrient use efficiency. This realization has created interest in integrating site-specific management technologies with automated irrigation systems. Center-pivot and linear-move irrigation systems provide a natural platform upon which to develop site-specific irrigation management technologies due to their current and increasing usage, large area of coverage, and relatively high degree of automation. Experimental center-pivot and lateral-move irrigation systems equipped to implement site-specific water management have been reported in the literature (Fraisse et al., 1995; Evans et al., 1996; King et al., 1996; Sadler et al., 1996; Harting, 1999; Perry et al., 2003; Moore et al., 2005; Chavez et al., 2006, Evans et al., 2007). The emphasis of these studies has been on control systems and hardware for achieving spatially variable water application along the irrigation system length. In each case, spatially variable water application was successfully achieved.

The application of chemicals through an irrigation system along with the water, known generically as chemigation, has been used for more than three decades as an effective means to economically and efficiently apply appropriately labeled chemicals (Threadgill, 1985; Lyle and Bordovsky, 1986). Intuitively, the ability to apply nitrogen fertilizer during the growing season according to crop needs minimizes the potential for N leaching from over-irrigation or untimely rainfall events. In-season application of nitrogen fertilizer through the irrigation system can increase nitrogen use efficiency, crop yield, and quality (Lauer, 1986, 1985; Westermann et al., 1988). Implementation of site-specific chemigation with center pivots has the potential to further increase fertilizer use efficiency by enabling the inherent spatial variability in nutrient requirements that develop throughout the growing season to be easily and efficiently addressed. The ability to address spatial variations in soil water availability and plant nutrient levels that develop during the season has the potential to conserve both water and

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fertilizer and reduce environmental contamination through improved management.

Experimental lateral-move and center-pivot irrigation systems equipped for spatially variable water application can potentially be used for spatially variable chemical application. Eberlein et al. (2000) evaluated site-specific herbigation using a 3-span linear-move irrigation system. Variable rate chemical application was accomplished by maintaining a constant concentration of chemical in the irrigation water and varying the depth of water application, thus the mass of chemical applied. When On/Off pulsing of sprinkler water flow is used as a means to achieve spatially variable water application (Fraisse et al., 1995; Evans et al., 1996; Harting, 1999; Perry et al., 2003; Moore et al., 2005; Chavez et al., 2006, Evans et al., 2007), maintaining a constant concentration of chemical in the water supply is difficult at best. The primary disadvantage of using spatially variable water application to achieve variable rate chemical application is that it results in creation of spatially variable soil water availability for the field. In arid regions, center-pivot and lateral-move irrigation systems are commonly designed with a capacity equal to or less than the peak water use rate of the crop. Soil moisture storage is relied upon to supply the needs of the crop through the peak use period. Thus, there is little, if any, opportunity during the peak crop water use period to implement variable rate chemical application without potentially creating soil water availability problems in the field that adversely impact crop yield and quality. This is unfortunate as this is the period during which nutrient uptake rate is normally the greatest and the most opportune time to apply crop nutrients to maximize use efficiency. The development of center-pivot irrigation systems capable of independent, spatially-variable water and chemical application would allow for in-season conjunctive and integrated management of water and nutrients necessary to maximize production efficiency and minimize the environmental impact of irrigated agriculture.

An independent chemical application system potentially offers additional advantages relative to current center-pivot irrigation and chemigation practices. Changing the sprinkler package nozzle sizes to reduce system flow rate and application rate at the beginning of the growing season to facilitate crop germination and establishment with less soil surface crusting has become a common practice in some areas. However, there is a lower limit of about a 50% reduction in system flow rate before water application uniformity is reduced below an acceptable level. An independent chemical application system could potentially be used early in the season to further reduce soil surface crusting from sprinkler irrigation to bare soil conditions. An independent chemical application system also offers the advantage of having less chemical mixed water to purge from the system at the end of an application. It may also provide further isolation of the chemical from the water source and reduce the environmental risk from chemigation.

The utility of lateral-move and center-pivot irrigation systems as a platform upon which to mount an independent chemical application system has long been recognized as such studies have been reported in the literature over the past three decades. Garvey (1981) patented a center-pivot attached spraying system that used conventional sprayer equipment and sprayer nozzles. Larsen (1980) and Taylor (1986) described a piggyback sprayer unit for a center-pivot irrigation system that applied 1600 L/ha (180 gal/acre) of chemical solution using broadcast no-drip sprayer nozzles. Lyle and Bordovsky (1986) designed and evaluated a Multi-Function Irrigation System (MFIS) which applied water with injected chemical through wide-angle nozzles at 3100 L/ha (340 gal/acre). The system provided good coverage throughout the canopy on corn, cotton, sorghum, and soybean that was superior to conventional chemigation or aerial application. However, because the system required the alignment of sprayer drop nozzles with the rows, the crop must be planted in concentric circles. Sumner et al. (1994) developed a Pivot-Attached Sprayer System (PASS) that used a single span center-pivot system only to mobilize an attached spray boom. The PASS was connected to a separate pressure pump and nurse tank for mixed chemicals or a chemical injection system with an appropriate water supply. The system used conventional sprayer parts and hardware for the spray boom. Similarly, Koegelenberg (1994) reported the development of a micro sprayer pest control system to piggyback on existing center pivots for added chemigation control. Economic analysis of the system showed it was comparable in cost to conventional ground based application. A low volume agro-chemical application system called the Accu-Pulse Precision Application has been commercialized by Valmont Industries (Valley, Nebr.). The Accu-Pulse system uses a proprietary spray applicator and has an application rate comparable with conventional ground-based application equipment. The system uses two supply tanks and pumps – one for water and the other for concentrated chemicals. Mixed chemical solution is transported along the center-pivot lateral by a 38-mm (1.5-in.) supply line. The spray applicators are attached to a 16-mm (0.625-in.) lateral line suspended below the sprinklers in each span along a cable strung between towers. Each lateral line is individually controlled. Farahani et al. (2006) evaluated spray applicator application pattern, discharge uniformity, and wetting coverage. They found discharge variation (CV) ranged from 13% to 34% at low application rates and the wetting coverage was in the range of 40%. Chemical application uniformity was not evaluated. The system is designed to provide uniform application of pesticides without concurrent application of irrigation water.

Each of the chemical application systems mounted on the irrigation system, with the exception of MFIS and Accu-Pulse, used conventional sprayer nozzles and components. Sprayer equipment is expensive and requires many hours to install, especially on a large center-pivot irrigation system. Sumner et al. (1995) used microirrigation sprinklers and polyethylene irrigation tubing and fittings to reduce the cost of their PASS. The redesigned PASS was installed on a single-span and 4-span center-pivot irrigation system. Components of the system included a chemical system mainline, solenoid valves, pressure regulators, drop pipes, check valves, and micro sprinklers. Normally closed solenoid valves located at each tower controlled flow from the chemical mainline to feeder lines of 19-mm (0.75-in.) polyethylene tubing. The valves were energized to discharge pesticide solutions only when the tower was moving. Pressure regulators were installed downstream from the solenoid valves to maintain the required pressure in each feeder line. Check valves were used at each micro sprinkler to prevent drainage of the feeder lines when the solenoid valve is closed. The design application rate was 1900 L/ha

(200 gal/acre) with the system operating at full speed (100 percentage timer setting). Measured chemical application uniformity of the PASS provided coefficient of uniformity (CU) values of 87% to 95%. The PASS was designed to provide uniform application of pesticides without concurrent application of irrigation water.

The development of lateral-move and center-pivot irrigation systems equipped for spatially variable water application and those equipped with an independent chemical application system have largely evolved independently. These developments need to be integrated to obtain irrigation systems capable of independent and concurrent spatially variable water and chemical application, but has received little attention. Increasing the utility of site-specific management technologies added to automated irrigation systems will increase their cost effectiveness and commercial potential. The objective of this study was to design and evaluate an independent spatially variable chemical application system on a center-pivot system equipped for spatially variable water application.

MATERIALS AND METHODS

The field study was conducted using a four-span 191-m (628-ft) long center pivot equipped for variable rate water application located at the University of Idaho Aberdeen Research and Extension Center (44.493° N, 112.973° W). King et al. (2005) and Wall and King (2005) provide details of the center-pivot system and the Distributed Control and Data Acquisition System (DCADAS) for real-time site-specific irrigation management. Variable rate water application along the center-pivot lateral is achieved using two parallel sprinkler packages sized with application rates of 1X and 2X. Solenoid actuated diaphragm valves on each sprinkler provide ON/OFF control of each sprinkler to obtain application rates of 0X, 1X, 2X, and 3X along the center-pivot lateral using ON/OFF sequencing of parallel sprinklers. The sprinklers are spinning plate spray sprinklers (S3000, w/D6 plates, Nelson Irrigation Corp., Walla Walla, Wash.). Each sprinkler is equipped with a 103-kPa (15-psi) fixed pressure regulator. Sprinkler spacing is 4.3 m (14.1 ft) for a given sprinkler package with a 1.4-m (4.7-ft) radial offset between sprinkler packages. The sprinklers are mounted on drop pipes at approximately 1.8 m (6 ft) above ground level. The last sprinkler is located inside the last tower and the center pivot is not equipped with an end gun or overhang beyond the last tower. Valve control is provided by a DCADAS that utilizes power line carrier and low-power radio frequency (RF) communication media to link system mounted controls and in-field stationary data loggers to a master control computer. The DCADAS consists of network nodes at each center-pivot tower for valve control and RF communications to upload logged soil water content and water application data from in-field sensors when the center-pivot lateral is within RF range. The data are stored at the master control computer located at the pivot point and downloaded to a portable computer for analysis and site-specific irrigation scheduling decisions.

Spinner-type, micro-irrigation sprinklers were selected for the chemical application system because they have a relatively large wetted diameter at low flow rates. This feature provides for high application uniformity when properly spaced and helps minimize start-stop movement effects of electric drive center-pivot irrigation systems on application uniformity. The Nelson S10 series mini-sprinkler (Nelson Irrigation Corp., Walla Walla, Wash.) were selected since they have a range of nozzle sizes available, can be inverted for use in an overhead application arrangement, and can be readily equipped with a combination pressure regulator and check valve to minimize flow fluctuation due to pressure variation and prevent chemical application system drainage. The general shape of the radial application rate pattern of the S10 mini-sprinkler with the gray spinner mounted inverted at a height of 1.5 m (5 ft) is shown in figure 1 for a range of nozzle sizes at 138 kPa (20 psi) (manufacturer 's data). The calculated application uniformity (CU) for a range of nozzle sizes at 138 kPa (20 psi) and 1.5- to 3.3-m (5- to 11-ft) range in sprinkler spacing is shown in figure 2. The S10 mini-sprinkler provides a calculated CU greater than 95% over the range in sprinkler spacing. A mini-sprinkler spacing of 2.6 m (8.6 ft) was selected for the chemical application system based on calculated CU and the desire to have an even number of mini-sprinklers in a 47.6-m (156-ft) center-pivot span length.

The control zone size along the center-pivot lateral for the chemical application system was selected as one-half span length or 23.8 m (78 ft), largely for convenience. This control

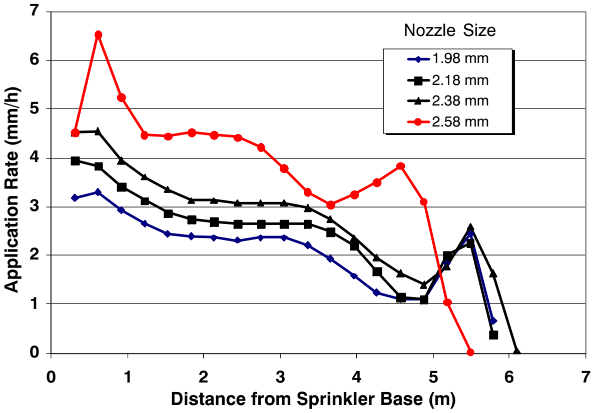

Figure 1. Radial application distribution profile for Nelson S10 mini-sprinkler with gray plate for a range of nozzle sizes at 138 kPa (20 psi) (manufacturer's data).

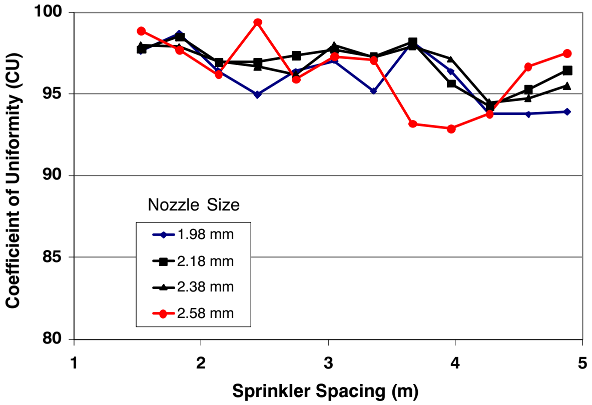

Figure 2. Calculated application uniformity (CU) for Nelson S10 mini-sprinkler with gray plate for a range of nozzle sizes and sprinkler spacings at 138 kPa (20 psi).

zone size is the same as that for variable rate water application and allows for use of a single drop pipe from a chemical supply line at each tower to supply chemical to two adjacent control zones. This control zone size allows for 0.08-ha (0.2-acre) maximum control resolution on a conventional 400-m (1323-ft) long center pivot when using one degree angular control system resolution. The first half of the first span was not equipped for variable rate chemical application (or water) due to the small area involved. A combination of nozzle sizing and ON/OFF pulsing is used to achieve uniform chemical application depth (water carrier) along the center-pivot lateral. Nozzle sizing and ON/OFF pulsing times used to achieve uniform application depth along the length of the four-span center pivot is given in table 1. The minimum water application rate (100 percentage timer setting) for the chemical application system is 16.8 L/min/ha (1.8 gpm/acre). Pulsing with less on-time than that shown in table 1 is used to achieve variable rate chemical application. The maximum chemical mass application rate is controlled by the chemical concentration in the water applied by the chemical application system.

The mini-sprinklers are attached to lateral lines made of 19-mm (0.75-in.) polyethylene (PE) tubing suspended along a steel cable strung between towers. Mini-sprinkler height is approximately 1.5 m (5 ft) above ground level. Each mini-sprinkler is equipped with a 138-kPa (20-psi) Nelson Mini Regulator Drain Check (MRDC) (Nelson Irrigation Corp., Walla Walla, Wash.). The 138-kPa (20-psi) MRDC stops flow at pressures below 103 kPa (15 psi) and regulates outflow pressure to 138 kPa (20 psi) at input pressures greater than 172 kPa (25 psi). A solenoid-actuated diaphragm valve (Irritrol 700B-.75, Irritrol, Riverside, Calif.) is used to control flow into each lateral line (control zone). Chemical mixed with water is supplied to each lateral line through a 50-mm (2-in.) PE chemical supply line secured to the top of the center-pivot lateral (fig. 3). The PE chemical supply line is weaved around the water sprinkler outlets such that it lies on alternate sides of the system lateral for adjacent outlets. The PE chemical supply line is rather loosely laid on the top of the center-pivot lateral to accommodate thermal expansion and contraction due to radiant heating and water cooling. A tee in the chemical supply line at each tower

Table 1. Specifications for chemical application system on four-span pivot.

	Span 1		Span2		Span 3		Span 4	
	Inner Half	Outer Half	Inner Half	Outer Half	Inner Half	Outer Half	Inner Half	Outer Half
Control zone number		1	2	3	4	5	6	7
Control zone length, m (ft)	–	23.8 (79)	23.8 (78)	23.8 (78)	23.8 (78)	23.8 (78)	23.8 (78)	23.8 (78)
Control zone start point, m (ft)	–	24.7 (81)	48.2 (158)	72.0 (236)	95.7 (314)	119.5 (392)	143.3 (470)	167.1 (548)
Control zone end point, m (ft)	–	48.2 (158)	72.0 (236)	95.7 (314)	119.5 (392)	143.3 (470)	167.1 (548)	190.9 (626)
Nozzle sizes, mm (in.)	–	1.98, 2.18, 2.38, 2.58 (.078, .086, .094, .102)	1.98, 2.18 (.078, .086)	1.98, 2.18 (.078, .086)	1.98, 2.18 (.078, .086)	2.18, 2.38 (.086, .094)	2.18, 2.38 (.086, .094)	2.38, 2.58 (.094, .102)
Uniform depth time on, %	–	27	49	69	88	100	100	100

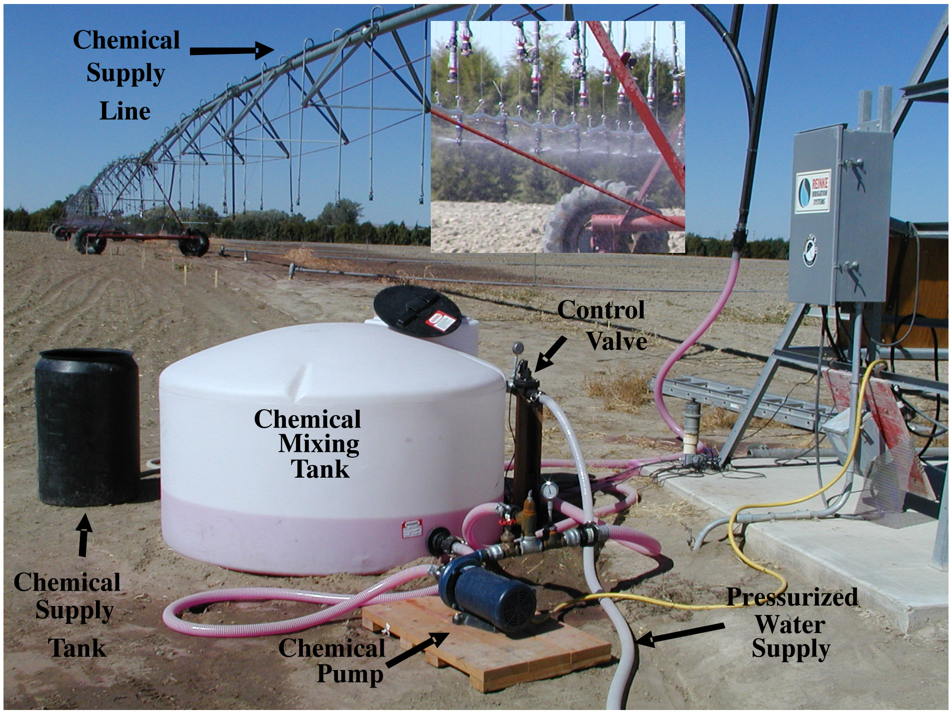

Figure 3. West view of independent chemical application system key components. Inset depicts lateral line and mini-sprinkler mounting used for independent chemical application.

supplies two lateral lines through a 50-mm (2-in.) PE drop pipe.

On-demand mixing is used to supply chemical-laden water to the chemical supply line. The mixing system was designed based on the assumption that a clean water supply of 265 Lpm (70 gpm) at 310-kPa (45-psi) minimum pressure is available during chemical application. This pressurized water source is assumed to be the same as that used for irrigation. However, it may need to be filtered due to the small nozzle sizes used with the mini-sprinklers. The mixing chamber is a 1900-L (500-gal) PE tank (fig. 3). A float switch is used to maintain a minimum amount of chemical solution available and limit the maximum amount to 1700 L (450 gal) to keep from over flowing the tank and causing a chemical spill. Water flow into the mixing tank is controlled using a 50-mm (2-in.) pressure regulated solenoid actuated diaphragm valve (ICV-201G with ACCU-SET pressure regulator, Hunter Industries, San Marcos, Calif.) (fig. 3). The flow rate into the mixing tank is controlled using an unsubmerged orifice. The orifice used is a 16.5-mm (0.65-in.) taper bore nozzle from a Nelson SR100 Big Gun (Nelson Irrigation Corp., Walla Walla, Wash.). The water source inlet pressure to the nozzle is regulated to 207-kPa (30-psi) to provide a controlled flow rate of 258 L/min (68 gpm) into the tank when the in-flow valve is open. A positive displacement diaphragm metering pump (Agri-Inject, Yuma, Colo.) is used to inject chemical into the water supply line between the control valve and nozzle (fig. 4). Operation of the chemical injection pump is electrically interlocked with the water supply control valve to only allow injection when the control valve is energized. The injection rate of the injection pump is used to control chemical concentration in the chemical supply stream. The on-demand mixing system operates independent of the DCADAS used to control variable rate chemical application rate along the center-pivot lateral. The chemical supply line is pressurized using a 2.2-kW (3-hp) centrifugal pump (Model DB1, Franklin Electric, Bluffton, Ind.) (fig. 3). An adjustable pressure relief valve between the pump and chemical supply line is used to limit maximum pressure in the chemical supply line and provide bypass flow return to the chemical mixing tank for agitation. A 50-mm (2-in.) diameter flexible hose 18 m (60 ft) in length is used connect the centrifugal pump to the chemical supply line laid on top of the center-pivot lateral (fig. 4). The flexible hose must be manually repositioned every 180 degrees of center lateral rotation to overcome winding around the center-pivot center tower.

The existing DCADAS software was modified to provide two 24-VAC outputs with pulse width modulation in place of simple ON/OFF control of 24-VAC outputs. The pulse width duration selected was 60 s. The timing of the outputs is optimized so that if possible only one output is energized at a given time to reduce the magnitude of flow rate changes in the chemical application system. For example, if the desired on times are 25 and 15 s for the two outputs, output one is energized for 25 s followed by 20 s of off time then output two is energized for 15 s. Both outputs are only energized simultaneously when the combined on-time for the two outputs (adjacent control zones at each tower) is greater than 60 s.

The application uniformity of the chemical application system cannot be evaluated using standard center-pivot methods (S436.1, *ASABE Standards,* 2004) because the discharge volume is too small to accurately measure with catch cans. Therefore, two other methods were used to evaluate the uniformity of chemical application. Chemical application uniformity was determined using an aircraft spray pattern sampling and analysis system, the WRK (WRK of Arkansas, Lonoke, Ark.) (Sumner et al., 1995). The WRK method uses a cotton string that absorbs spray droplets containing Rhodamine WT fluorescent dye (Whitney and Roth, 1985). The string reflectance is measured on a Sequoia-Turner filter fluorometer with a WRK string door and built-in communication hardware and software.

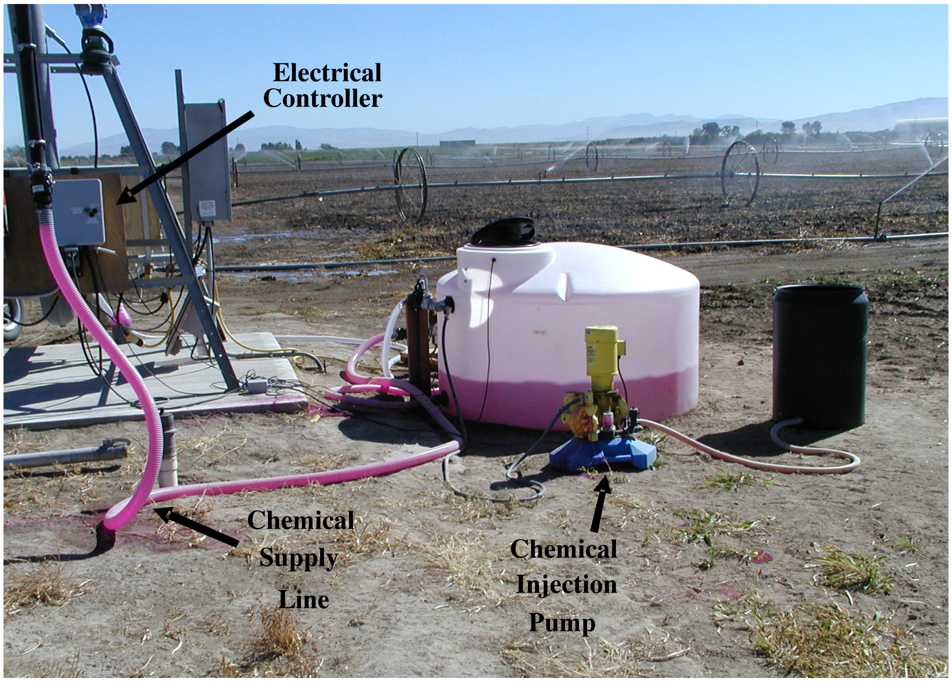

Figure 4. East view of independent chemical application system key components.

Numerical fluorometer readings of zero to 100 are obtained from the string at approximately 13.4-cm (5.3-in.) intervals. The fluorometer readings are called “relative application values” and represent the amounts of dye (chemical laden water) applied at distances along the length of the string. The CU was calculated for the chemical application system using the relative application values in the standard equation for center pivots (S436.1, *ASABE Standards,* 2004). This method was used to evaluate chemical application uniformity for both uniform and variable rate chemical application along the center-pivot lateral. For each field test, two radial lines of string were suspended 30 cm (1 ft) above ground level under each center-pivot span. The spatially variable chemical application rates evaluated are listed in table 2.

Chemical application uniformity was also evaluated by measuring the mass of chemical applied with concurrent irrigation. Two lines of catch cans with 2.4-m (8-ft) spacing between adjacent cans in a radial line were used to measure water volume applied. The catch cans, measuring 15.2 cm (6 in.) in diameter and 20.3 cm (8 in.) in height were placed on the ground and leveled by sight. Rodamine WT dye was applied through the chemical application system at uniform and spatially variable application rates concurrent with uniform irrigation water application along the center-pivot lateral. Water volume in each catch can was measured using a 1000-mL graduated cylinder. A 125-mL water sample from each catch can was collected and stored at 4°C until analyzed. The concentration of Rhodamine WT dye in each water sample was measured with a fluorometer (Turner Designs, TD-7000, Sunnyvale, Calif.) The mass of dye in each catch can was calculated based on the measured water volume and measured dye concentration. The CU for dye mass applied was calculated and used to evaluate chemical application uniformity with concurrent water application. The spatially variable chemical application rate patterns evaluated are listed in table 3.

RESULTS AND DISCUSSION

The chemical application distribution profile for test #1 (table 2) determined with the WRK string method is shown in figure 5. The calculated composite CU for the two string lines was 90.0. Application uniformity tends to increase toward the end of the system lateral in control zones 5, 6, and 7 where the sprinklers were on 100% of the time (table 1). The solenoid actuated diaphragm valves used to control application rate by pulsing flow ON/OFF have a greater time interval for closing than opening. A 1.5-s difference between opening and closing time was included in the calculation of the electrical on-time required to achieve the specified application rate. This time difference is somewhat variable between valves and can lead to errors in actual application rate. Closing of the MRDC for each mini-sprinkler was found to be susceptible to foreign material in the water supply. Clean well water was used as the water supply but material that entered the chemical delivery system during installation initially created some problems. It became apparent that trapped air in the chemical lateral lines resulted in variable closing times for the MRDCs along a lateral line. The MRDC(s) with the lowest closing pressure (due to manufacturing differences) were the last to close. Expansion of the trapped air after the diaphragm valve closed caused the MRDC(s) with the lowest closing pressure to close more slowly, leading to non-uniform chemical application along the lateral line. The time difference between closing of the MRDCs along a lateral line was less than 2 s but it is cumulative and can amount to 1-2 min as the center-pivot lateral passes over an application point. Trapped air was bled from the lateral lines on system startup, but high points along the lateral lines made it difficult to purge all trapped air.

The chemical application distribution profile for test #2 (table 2) determined with the WRK string method is shown in figure 6. For this test the center-pivot percentage timer was set at 50% and ON/OFF pulsing was used in all control zones to achieve uniform chemical application rate along the center-pivot lateral. The calculated composite CU for the two string lines was 84.1. Application uniformity in control zones 5, 6, and 7 was similar to that of control zones 1 through 4. This is attributed to the action of ON/OFF pulsing flow in the chemical lateral lines for control zones 5, 6, and 7 in this test. This result suggests that variability in valve and MRDC closing times substantially reduces application uniformity

Table 2. Control zone target relative application rates for chemical application system uniformity tests using WRK measurements.

		Span 1		Span 2		Span 3		Span 4	
Test ID	Percentage Timer Setting (%)	Inner Half (%)	Outer Half (%)	Inner Half (%)	Outer Half (%)	Inner Half (%)	Outer Half (%)	Inner Half (%)	Outer Half (%)
1	100	–	100	100	100	100	100	100	100
2	50	–	100	100	100	100	100	100	100
3	100	–	100	25	100	50	100	25	100
4	50	–	100	25	100	50	100	25	100
5	100	–	25	100	50	100	25	100	50

Table 3. Control zone target relative application rates for chemical application system uniformity tests concurrent with irrigation water application.

		Span 1		Span 2		Span 3		Span 4	
Test ID	Percentage Timer Setting (%)	Inner Half (%)	Outer Half (%)	Inner Half (%)	Outer Half (%)	Inner Half (%)	Outer Half (%)	Inner Half (%)	Outer Half (%)
A	50	–	100	100	100	100	100	100	100
B	50	–	100	25	100	50	100	25	100

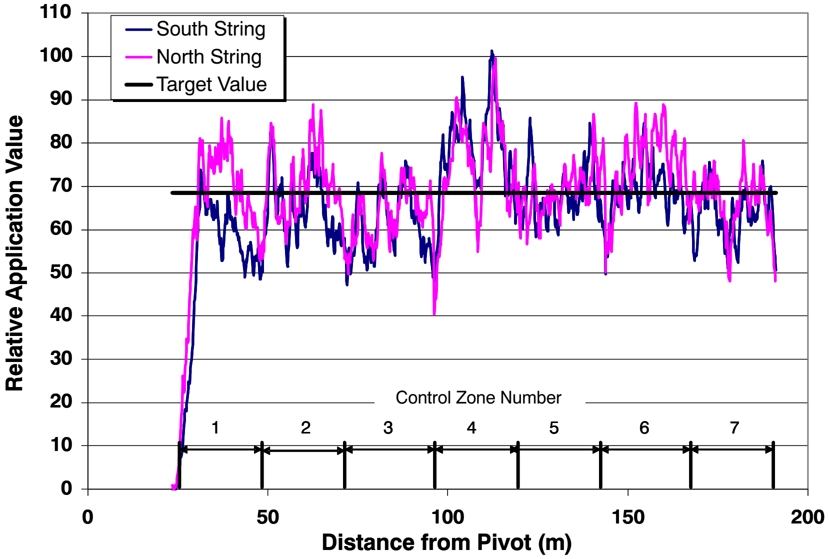

Figure 5. Application distribution profile of test #1 determined with the WRK string method. Composite CU for the two string lines is 90.0 between 30 and 190 m (98 and 623 ft). Percentage timer setting 100% and control zones 1 through 4 pulsing on-off.

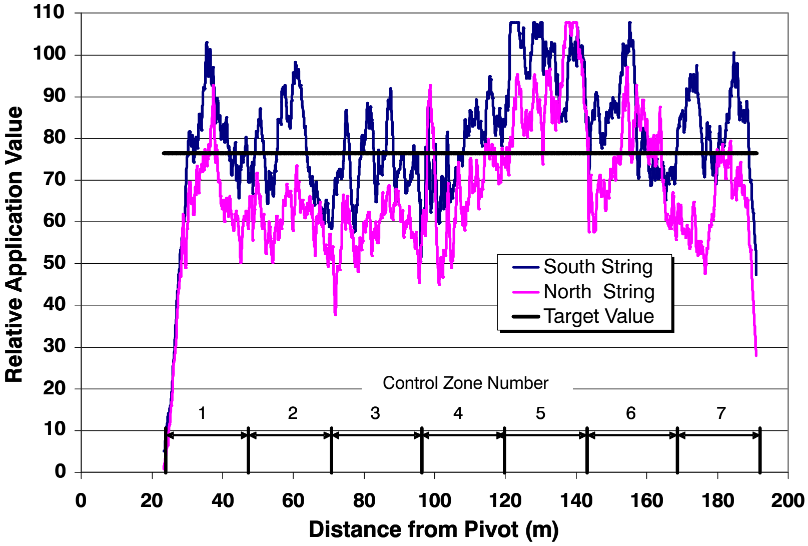

Figure 6. Application distribution profile of test #2 determined with the WRK string method. Composite CU for the two string lines is 84.1 between 30 and 190 m (98 and 623 ft). Percentage timer setting 50% and all control zones pulsing on-off.

relative to that attainable by the mini-sprinklers at the selected sprinkler spacing. Achieving and sustaining high chemical application uniformity will require use of control valves and check valves that have constant and reliable opening and closing times. The high relative application under control zone 5 indicates that the chemical lateral line valve was on more than intended for some undetermined reason.

The lower calculated CU for test #2 relative to test #1 is due in part to the difference in relative application values between the two parallel string lines. This difference is attributed to a shift in wind direction during the test. Wind direction at a weather station within 1.6 km (1 mi) of the study site ranged from ENE-SSW-SW-S-SSE-S and wind speed ranged from 0.98 to 3.1 m/s (2 to 7 mph) during the test. The center-pivot lateral was aligned pointed west and moved counter clockwise during the test to WSW alignment. The small droplet sizes of the mini-sprinkler are very susceptible to wind drift. The wind change to S-SSE-S near the end of the test caused drifting toward the southern string after the center-pivot lateral had passed over.

The application distribution profile for test #3 (table 2) determined with the WRK string method is shown in figure 7. Chemical application rate was varied along the center-pivot lateral as listed in table 2. The composite CU and mean relative application values for a 10-m (33-ft) mid-section of each control zone is shown in table 4. The composite CU values ranged from 85.5 to 92.1 over the seven control zones. The ability of the chemical application system to achieve variable target application rates along the system lateral can be separated into two functions. The first function is how well the DCADAS does at providing the correct ON/OFF cycling times combined with operation of the diaphragm valve on each control zone. The second function is how evenly the

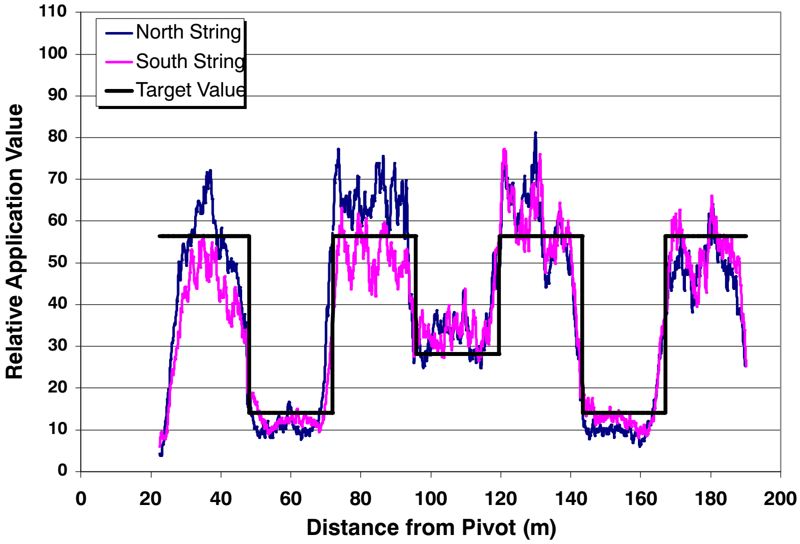

Figure 7. Application distribution profile of variable rate chemical application test #3 determined with the WRK string method. Percentage timer setting 100% and control zones 1, 2, 3, 4, and 6 pulsing on-off.

sprinklers and associated components (MRDC) distribute water within a control zone for a given target application rate. Extraneous factors affecting both functions are foreign material in the water supply, wind, trapped air in the lateral lines and sampling error. Functioning of the DCADAS and diaphragm valve can be evaluated based on the measured area-weighted mean application value in the midsection of the control zone relative to the target value. Functioning of the sprinklers can be evaluated based on the degree of area-weighted variability about the measured area-weighted mean application e.g. CU. The CU values listed in table 4 are a measure of sprinkler performance along the midsection of a control zone. Regression analysis of a 1:1 relationship between area-weighted mean relative application values in the 10-m (33-ft) midsection of each control zone and the target relative application values is shown in figure 8. The regression coefficient (R^2) is 0.95 for the 1:1 relationship. Thus, 95% of the variability in measured area-weighted mean relative application values is due to the variable rate chemical application system applying the target value.

The chemical application distribution profile for test #4 (table 2) determined with the WRK string method is shown in figure 9. The chemical application rate along the center-pivot lateral was varied as listed in table 2. The difference between test #4 and test #3 is 50% slower travel speed. The composite CU and area-weighted mean relative application value for a 10-m (33-ft) midsection of each control zone are shown in table 4. The composite CU values ranged from 83.7 to 93.0 over the seven control zones.

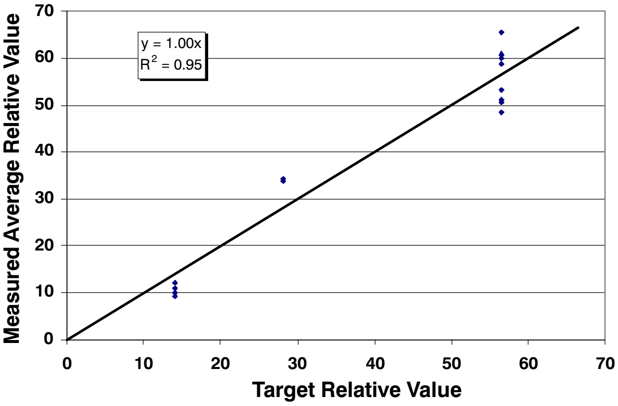

Figure 8. Measured area weighted mean relative application value determined with the WRK string method compared with target relative application value for 10-m (33-ft) midsection of each control zone for test number 3.

Table 4. Target application, composite CU and weighted mean relative application values in each control zone midsection for variable rate chemical application tests using the WRK string method.

	Span 1		Span 2		Span 3		Span 4	
	Inner Half	Outer Half	Inner Half	Outer Half	Inner Half	Outer Half	Inner Half	Outer Half
Control Zone Number		1	2	3	4	5	6	7
Test #3								
Target Application (%)	–	100	25	100	50	100	25	100
Weighted mean	–	54.7	11.6	59.4	34.1	59.4	10.7	50.9
CU	–	88.0	88.6	89.3	92.1	88.0	85.5	90.6
Test #4								
Target Application (%)	–	100	25	100	50	100	25	100
Weighted mean	–	44.1	6.7	45.0	24.5	55.1	8.1	48.1
CU	–	86.8	91.5	93.0	83.7	90.0	91.8	87.6
Test #5								
Target Application (%)	–	25	100	50	100	25	100	50
Weighted mean	–	8.0	45.0	10.9	52.4	10.6	44.4	19.7
CU	–	82.9	88.6	85.4	88.9	78.5	90.3	87.8

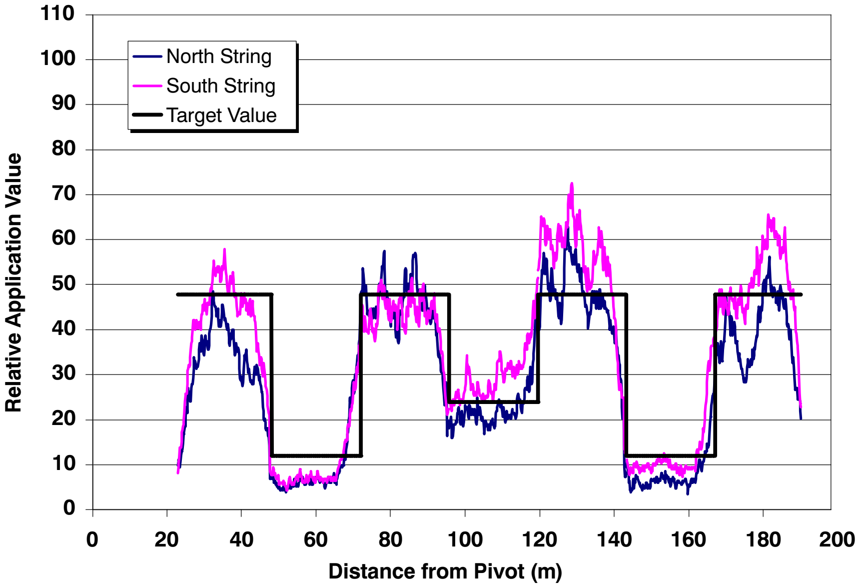

Figure 9. Application distribution profile of variable rate chemical application test #4 determined with the WRK string method. Percentage timer setting 50% and all control zones pulsing on-off.

Regression analysis of a 1:1 relationship between area-weighted mean relative application values in the 10-m (33-ft) midsection of each control zone and the target relative application values results in a R^2 of 0.91. The lower R^2 is attributed to sprinkler pulsing in control zones 5 and 7 to achieve the target application rates in these zones with the slower travel speed of the center-pivot system.

The application distribution profile for test #5 (table 2) determined with the WRK string method is shown in figure 10. Chemical application rate was varied along the center-pivot lateral as listed in table 2. The composite CU and mean relative application values for a 10-m (33-ft) mid-section of each control zone is shown in table 4. The composite CU values ranged from 78.5 to 90.3 over the seven control zones. The lower CU values for control zone 1 and 5 are due to the difference in relative application values between the two string lines. The individual CU values were 92.4 and 90.0 for control zone 1 and 89.8 and 91.5 for control zone 5. Regression analysis of a 1:1 relationship between area-weighted mean relative application values in the 10-m (33-ft) midsection of each control zone and the target relative application values results in a R^2 of 0.90.

The water distribution application profile of the variable rate irrigation system for a uniform water application (test A, table 3) determined using catch cans is shown in figure 11. The composite CU for uniform water application was 89.6 between 30 and 190 m (98 and 623 ft) along the center-pivot lateral. The average area-weighted mean application depth was 12.1 mm (0.48 in.). Water application was slightly less under the first span of the center pivot by design as this area commonly exhibits over-irrigation relative to the rest of the system.

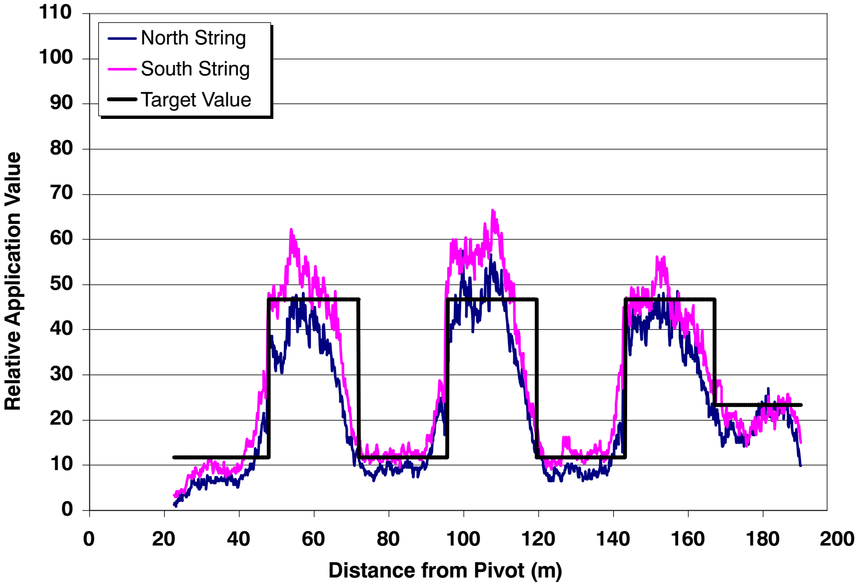

Figure 10. Application distribution profile of variable rate chemical application test #5 determined with the WRK string method. Percentage timer setting 100% and all control zones except control zone 6 pulsing on-off.

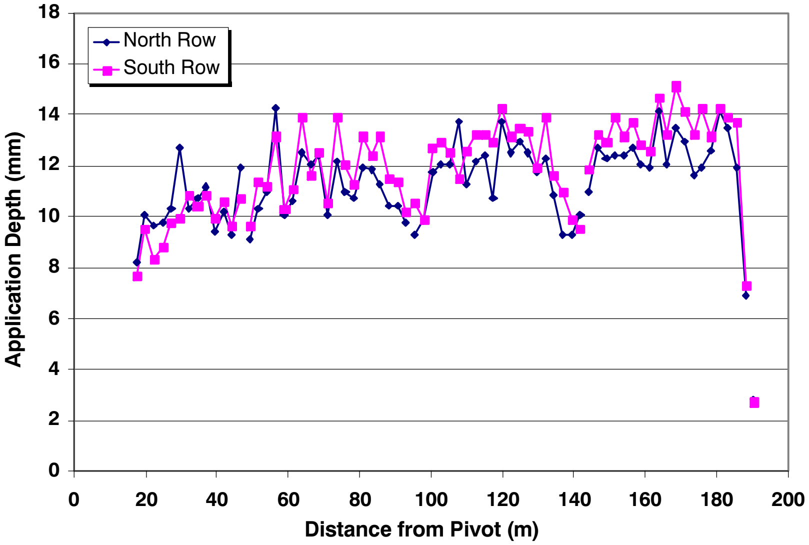

Figure 11. Water application distribution profile of test A determined with catch cans. Composite CU of the two rows of catch cans was 89.6 between 30 and 190 m (98 and 623 ft). Percentage timer setting 50% and control zones 1 through 4 pulsing on-off. Mean application depth was 11.7 mm.

The chemical application profile for concurrent uniform water and chemical application (test A, table 3) determined using catch cans is shown in figure 12. Composite CU for the two rows of catch cans was 88.6 between 30 and 190 m (98 and 623 ft) along the center-pivot lateral. For this center-pivot system, the addition of the independent chemical application system for uniform chemical application reduced application uniformity one percentage point over conventional chemical application through the irrigation water. This is a small trade off for the capability of independent variable rate chemical application.

The water distribution application profile of the variable rate irrigation system for a uniform water application and variable rate chemical application (test B, table 3) determined using catch cans is shown in figure 13. The composite CU for uniform water application was 89.2 between 30 and 190 m (98 and 623 ft) along the center-pivot lateral. The average area-weighted mean application depth was 12.3 mm (0.48 in.). The spatially variable water application depths created by spatially variable chemical application had little effect on water application uniformity.

The chemical application profile for concurrent variable rate chemical application and uniform water application (test B, table 3) determined using catch cans is shown in figure 14. The relative chemical application rates were varied along the center-pivot lateral as listed in table 3. The measured relative application rates are close to the target rates relative rates at 25% and 50%. However, there was considerable variability in the 100% target relative rates. This degree of variability was not present in the uniform application test. The actual cause of this variability is unknown but likely the result of water dripping from the mini-sprinklers into the catch cans and/or trapped air which caused uneven timing of MRDC closing along the lateral lines. Regression analysis of

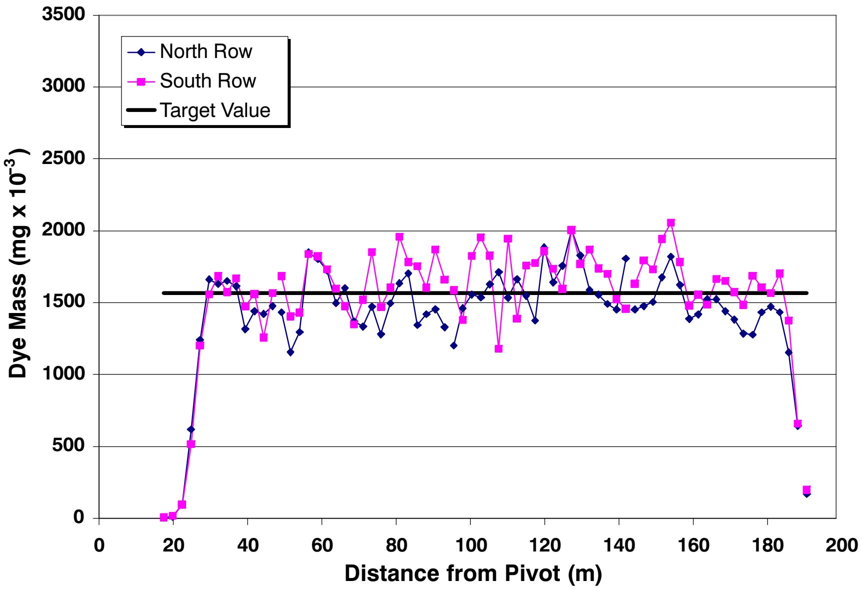

Figure 12. Chemical application distribution profile of test A determined with catch cans. Composite CU of the two rows of catch cans was 88.6 between 30 and 190 m (98 and 623 ft). Uniform water and chemical application test. Percentage timer setting 50% and control zones 1 through 4 pulsing on-off.

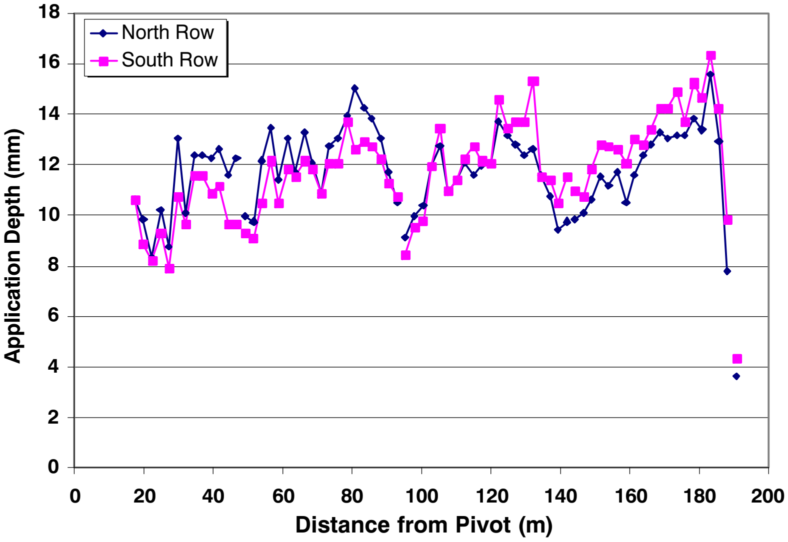

Figure 13. Water application distribution profile of test B determined with catch cans. Composite CU of the two rows of catch cans was 89.2 between 30 and 190 m (98 and 623 ft). Uniform water and variable chemical application test. Percentage timer setting 50% and control zones 1, 2, 3, 4, and 6 pulsing on-off. Mean application depth was 12.5 mm.

a 1:1 relationship between area-weighted mean relative application values in a 9.8-m (32-ft) midsection of each control zone and the target relative application values results in a R^2 of 0.98 (fig. 15). Thus, 98% of the variability in measured area-weighted mean application values is due to the variable rate chemical application system applying the target value.

Summary

An independent chemical application system capable of variable rate application was installed and tested on a 4-span center-pivot irrigation system equipped for variable rate water application. The chemical application system was assembled using mini-sprinklers and common commercial irrigation system components. For uniform chemical application the CU values ranged from 84 to 90 providing acceptable application uniformity. For variable rate chemical application, CU values ranged from 78.5 to 93.0 and measured mean area-weighted relative application values were well correlated with target relative application values with R^2 of 0.9 or higher. The chemical application system is capable of spatially variable chemical application concurrent and independent of spatially variable water application. Functionality of the independent chemical application system was found to be susceptible to foreign material in the water supply and trapped air in lateral lines. For water supplies other than well water, filtering may be required. Air relief valves are needed at high points and at the end of lateral lines to adequately purge trapped air. The valves used to ON/OFF pulsing of the chemical application system lateral lines need to have reliable and consistent opening and closing times in order to attain target application rates.

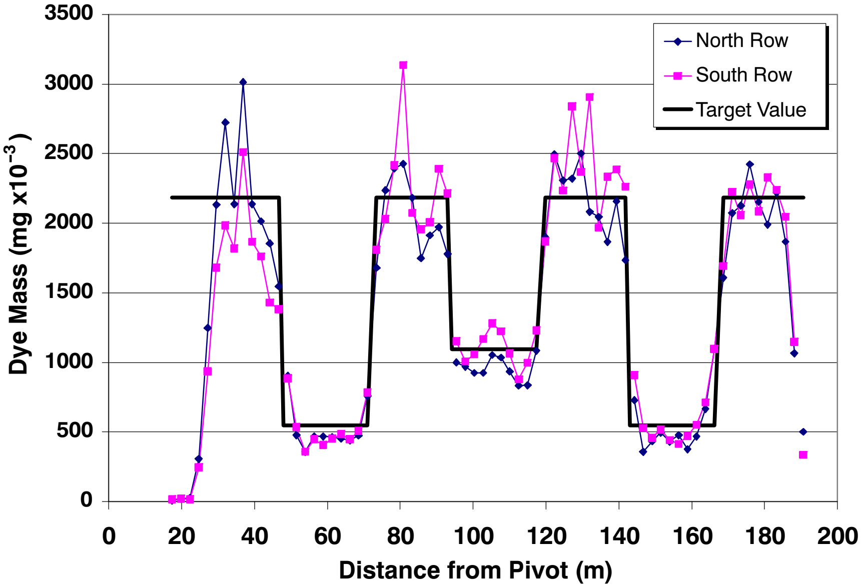

Figure 14. Chemical application distribution profile of test B determined with catch cans. Percentage timer setting 50% and control zones 1, 2, 3, 4, and 6 pulsing on-off.

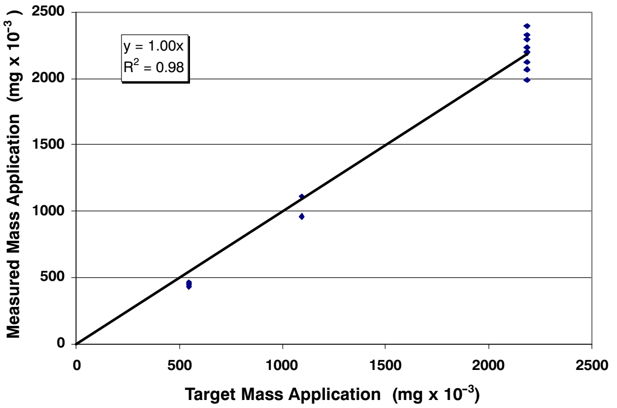

Figure 15. Measured area weighted mean mass application determined with catch cans compared with target mass application for 9.8-m (32-ft) midsection of each control zone.

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