

SPATIALLY DISTRIBUTED CONTROL NETWORK FOR FLOW PROPORTIONAL CHEMICAL INJECTION WITH CENTER PIVOT SPRINKLER IRRIGATION

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ABSTRACT. *The agricultural production practice of injecting a chemical into an operating irrigation system and applying it to the field area with the water is known as chemigation. Chemigation is a widely adopted practice with center pivot sprinkler irrigation. However, the practice of chemical injection at a constant rate with center pivot sprinkler irrigation systems equipped with an end gun and/or swing-arm corner watering system results in systematic chemical application errors ranging from 7% to 21% due to systematic changes in system flow rate. Chemical injection proportional to center pivot sprinkler system flow rate is one approach to reduce systematic chemical application errors. The objective of this project was to test the feasibility of using real-time monitoring of center pivot sprinkler irrigation system operating status to control chemical injection rate proportional to calculated system flow rate, thus minimizing systematic chemical application errors. A spatially distributed control network was developed to facilitate real-time monitoring of end gun and swing-arm corner watering system operating status and pressure. The spatially distributed control network consisted of three network nodes at specific locations along a center pivot sprinkler irrigation lateral that used the 480 VAC 3-phase power cable on the center pivot sprinkler irrigation system as the communication medium. The spatially distributed control network was installed on a commercial 460-m (1510-ft) long center pivot sprinkler system equipped with an end gun and swing-arm corner watering system. Performance of chemical injection proportional to calculated flow rate based on real-time center pivot sprinkler irrigation system operating status was evaluated by injecting Rhodamine WT dye into the center pivot sprinkler irrigation system water supply and measuring its concentration in the applied water. Mean dye concentration varied by 26% under constant rate chemical injection and 2% under flow proportional chemical injection due to systematic changes in center pivot sprinkler irrigation system flow rate. Use of the flow proportional chemical injection system reduced the coefficient of variability in measured dye concentration of applied water by 54% from 0.100 to 0.046. Use of the spatially distributed control network for calculating center pivot sprinkler system flow rate eliminates the need for straight sections of unobstructed piping at the chemical injection site. Display and/or data logging of real-time center pivot sprinkler operating status is an added benefit of using the spatially distributed control network. This information provides the ability to monitor, diagnose, and troubleshoot center pivot sprinkler system operation. Commercialization and adoption of the technology could reduce systematic chemical application errors and facilitate maintenance and operation of center pivot sprinkler irrigation systems equipped with an end gun and/or swing-arm corner watering system.*

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

The agricultural production practice of injecting a chemical into an operating irrigation system and applying it to the field along with the water is generically known as chemigation (Threadgill, 1985).

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Chemigation is an effective means of economically and efficiently applying chemicals (Bynum et al., 1991; Sumner et al., 1991; Archer et al., 1991; Barnes et al., 1992; Weissling et al., 1992; Chandler and Sumner, 1993; Chalfant et al., 1993; Culbreath et al., 1993; Chandler et al., 1994; Brennehan et al., 1994; Waller et al., 1995; Hamm and Clough, 1999). When practiced with center pivot sprinkler irrigation, the primary advantages of chemigation include high application uniformity of applied chemical, timeliness of applying the chemical when needed, and avoidance of compaction and crop damage caused by conventional ground-based application equipment (Threadgill, 1985). Intuitively, the ability to periodically apply nitrogen fertilizer during the growing season according to crop need minimizes the potential for nitrogen leaching from over-irrigation or untimely rainfall events. The advantages of chemigation such as timing and frequency of application can make it part of a nitrogen Best Management Practice (BMP) for various crops (Scherer et al., 1999; Lamm et al., 2004). Beyond environmental advantages, in-season application of nitrogen fertilizer through the irrigation system can increase nitrogen use efficiency, crop yield, and

quality. For example, application of nitrogen fertilizer after potato tuber initiation has been shown to increase marketable yield while increasing nitrogen use efficiency (Lauer, 1986, 1985; Westermann et al., 1988; Errebhi et al., 1998). In 1998, 35% of irrigated farms in the United States reported using chemigation for fertilizer application and 7% of irrigated farms reported using chemigation for chemical application (USDA, 1998).

High chemical application uniformity is a commonly cited advantage of chemigation with center pivot sprinkler irrigation (Threadgill, 1985). However, three criteria must be met in order to attain high chemical application uniformity using chemigation with center pivot sprinkler irrigation systems.

- Water application uniformity must be high by having a properly designed and installed sprinkler package as well as regular maintenance and visual inspection to correct clogging, nozzle wear, and pressure regulator failure.
- Travel speed of the system must be uniform across the field area by avoiding rutting and wheel slippage or significant differences in speed traveling uphill versus downhill.
- The chemical injection rate must be proportional to system flow rate to provide constant chemical concentration in the applied irrigation water.

This third criterion is not necessarily met in practice when use of end guns and/or swing-arm corner watering systems cause the water flow rate to change while the injection rate remains constant. This results in systematic chemical application errors due to the variable wetted radius of the irrigation system.

Eisenhauer and Bockstadter (1990) analyzed chemical application errors for center pivots equipped with a pressure regulated sprinkler package and an end gun and/or swing-arm corner watering system. They developed a series of equations to calculate average (area weighted) chemical application error for constant chemical injection rate with center pivot sprinkler irrigation systems. Based on the equations presented by Eisenhauer and Bockstadter (1990), average chemical application error for a center pivot sprinkler system equipped with an end gun located in the center of a square 65-ha (160-acre) field where the effective wetted radius of the system lateral is 396 m (1300 ft) with the end gun off and 427 m (1400 ft) with the end gun on, is 7.5% with a maximum error of 8.3%. Average chemical application error increases as the size of the square field area decreases and the end gun effective radius remains the same. Eisenhauer and Bockstadter (1990) calculated an average chemical application error for a pressure-regulated sprinkler package on a 390-m (1279-ft) center pivot sprinkler lateral equipped with an 80-m (262-ft) swing-arm corner watering system and an end gun with an effective radius of 20 m (66 ft) of 16% with a maximum error of 21%. This relatively high degree of variability in chemical application with center pivots equipped with a swing-arm corner watering system is rarely corrected or sometimes even recognized.

Proportional chemical injection systems are currently on the market that can be adapted to center pivot sprinkler irrigation systems but they are relatively expensive. These systems utilize a flow meter to measure the flow rate of the center pivot. The measured flow rate is then used to compute the chemical injection flow rate needed to maintain a set flow

proportional injection rate. Modulating the speed of a motor or the stroke of the metering pump achieves the computed chemical injection flow rate. These systems work well when they are included in the initial design of the piping systems for turf irrigation, wastewater treatment, and industrial processes. However, their performance can be impaired when installed after the fact due to the presence of elbows, tees, and flow control valves which can create asymmetrical flow profiles and flow rotation. Closed conduit flow meters perform best when flow profiles are symmetric and do not rotate (James, 1988). Standard installation requirements for flow meters generally require unobstructed flow for a distance equivalent to 5 to 50 pipe diameters upstream and 5 to 10 pipe diameters downstream of the flow meter (James, 1988). Johnson et al. (2001) reported flow measurement accuracy's for an ultrasonic flow meter of $\pm 5\%$ when installed 10 pipe diameters downstream of flow disturbances and $\pm 36.5\%$ when installed close to flow disturbances. Water supply connections for center pivot sprinkler irrigation systems often do not include 10 to 60 pipe diameters in unobstructed flow length needed for accurate flow measurement. Neglected maintenance and the harsh outdoor environment can lead to calibration drift. Flow meters do not withstand the freezing and thawing cycles of cold climates and after a few years the bearings and other moving parts degenerate rendering the flow measurement device inoperable (Hla and Scherer, 2001).

The flow rate of a center pivot sprinkler irrigation system equipped with pressure regulators can be estimated based on knowledge of system operating pressure and sprinkler nozzle sizes. We hypothesize that by using spatially distributed control network technology for real-time measurement of end gun operating status and pressure and the operating status of valves along a swing-arm corner watering system, system flow rate can be calculated for pressure regulated sprinkler packages and subsequently used to control flow proportional chemical injection. This may allow for greater accuracy than using a flow meter, and at less cost and easier installation. The objective of this research was to evaluate the feasibility of using spatially distributed control network technology to control a flow proportional chemical injection system to minimize systematic chemical application errors.

MATERIALS AND METHODS

A spatially distributed control network was developed for a center pivot sprinkler system by using the 480 VAC 3-phase power cable on the center pivot sprinkler irrigation system as the communication medium. The spatially distributed control network consisted of three network nodes operating in a master-slave configuration. The master network node was located at the pivot point and used to display current center pivot sprinkler operating state, log operational data at 5-min intervals, and control the flow rate of the chemical injection pump. One network slave node was located on the center pivot sprinkler lateral at the corner watering system swing joint and used to collect swing-arm sprinkler valve operating state and GPS location. The second network slave node was located on the center pivot sprinkler lateral at the drive wheel tower of the swing-arm and used to monitor pressure there and hence the operating status of the end gun.

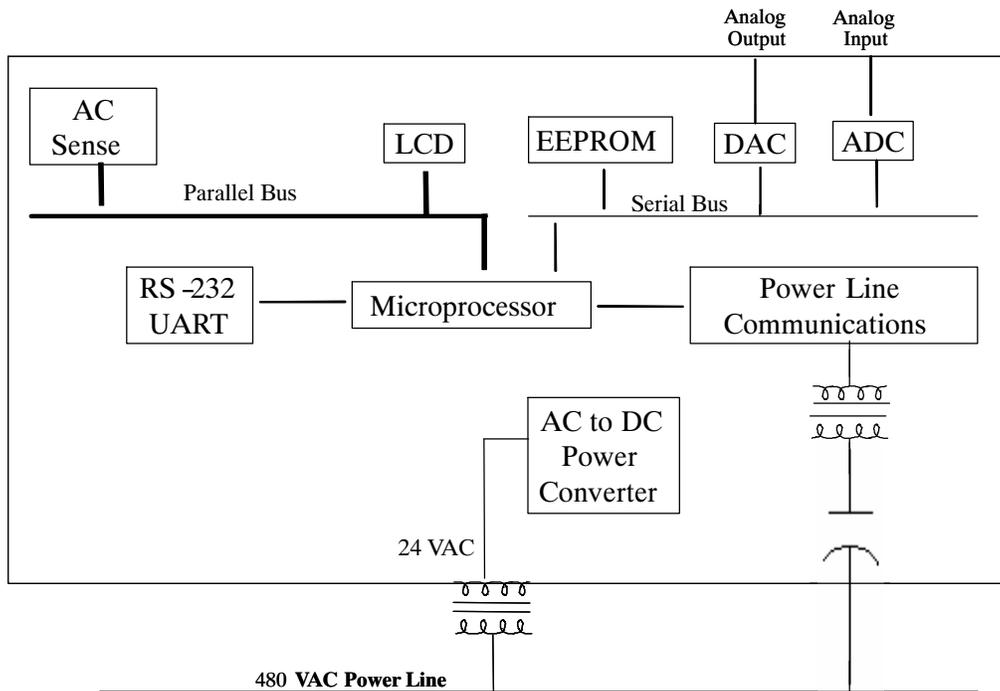


Figure 1. Block diagram of the PCB for network node that are fixed to the center pivot system and used for monitoring real-time operating status.

The electronic hardware for the control network was a single printed circuit board (PCB) that can function as either a master or slave network node. A block diagram of the key elements of the PCB is shown in figure 1. Power for the PCB is obtained from the 480-VAC power line using an external step-down transformer to provide nominal 24 VAC. Digital communications on the 480-VAC power line is implemented using proprietary integrated circuit chips from CEBUS (SSC P300 and SSC P111, Intellon Corp., Ocala, Fla.). A serial bus designed for communications between integrated circuits is used on the PCB for data transfers between the microprocessor and power line carrier interface. The same serial bus is used for data transfers between the microprocessor, EEPROM, a single-channel 10-bit DAC, and a single channel 10-bit ADC. A parallel bus on the PCB is used for data transfer between the microprocessor and a two-line, 16-character liquid crystal display (LCD) and sixteen 120-VAC sensing inputs. The AC sensing inputs are used to determine operating status of the sprinkler valve controller on the center pivot sprinkler swing arm. An asynchronous RS-232 serial interface provides for data transfer between a computer and other RS-232 serial devices such as a GPS receiver (GPS 17 HVS, Garmin International Inc., Olathe, Kans.) Software installed on the microprocessor determines whether the PCB functions as a master or slave network node. Based on real-time center pivot sprinkler system operating status collected using the spatially distributed control network, system flow rate was calculated as the sum of flow from each sprinkler along the center pivot sprinkler lateral up to the swing-arm joint, plus flow from each individual sprinkler on the swing-arm that was turned on, plus the flow from the end gun. Flow from the end gun was calculated based on verified nozzle size and measured pressure at the outlet of the booster pump.

The rate of chemical injection was controlled using a 0- to 5-VDC analog output from the master network node to control the motor speed of a positive displacement chemical

injection pump (mRoy A/P, Agri-Inject, Inc., Yuma, Colo.) using a variable frequency drive (VLT MICRO 176F7312, Danfoss Drives, Loves Park, Ill.). Analog voltage output from the master node was determined based on calculated flow rates of the center pivot sprinkler irrigation system. The analog voltage output, A_{out} , was calculated based on real-time calculated flow rate of the center pivot sprinkler irrigation system, Q_c , and maximum calculated system flow rate, Q_{max} , as:

$$A_{out} = 5 \cdot \frac{Q_c}{Q_{max}} \quad (1)$$

The spatially distributed control network was installed on a 10-span, 460-m (1510-ft) long center pivot sprinkler irrigation system equipped with an end gun and swing-arm corner watering system located near American Falls, Idaho, in May 2004. The field was planted to winter wheat. The center pivot sprinkler package was equipped with 138-kPa (20-psi) pressure regulators on each sprinkler to minimize variations in water application depth due to pressure fluctuations caused by multiple irrigation systems connected to the same water supply, and changes in flow rate and elevation as the center pivot sprinkler lateral traversed the field area. The nozzle size of every sprinkler on the system was determined by visual inspection. Based on the sprinkler manufacturer's nozzle flow rate data, the total design maximum flow rate of the center pivot sprinkler system was calculated as 4875 L/min (1288 gpm). The total maximum design flow rate of the swing-arm corner watering system and end gun combined was calculated as 1927 L/min (509 gpm) or 39.6% of total system flow rate. Constant rate chemical injection into this system can result in a 39.6% variation in chemical application rate between full extension and retraction of the swing-arm corner watering system and end gun operation.

Rhodamine WT dye was injected through the irrigation system to evaluate performance of the flow proportional chemical injection system. The dye was applied through the chemical injection system at a constant rate for one center pivot sprinkler system revolution beginning 5 June 2005 and at a flow proportional rate for one system revolution beginning 30 June 2005. Catch cans measuring 15.2 cm (6 in.) in diameter and 20.3 cm (8 in.) in height were placed on the ground within the crop canopy to collect water samples for dye concentration analysis. Crop canopy was fully developed and approximately 76 cm tall for both tests. The catch cans were placed at 5° angular increments around the field adjacent to the 7th center pivot tower wheel track. A 125-mL water sample from each catch can was collected and stored at 4°C until the dye concentration could be measured with a fluorometer (TD-7000, Turner Designs, Sunnyvale, Calif.). Water samples were collected twice daily at around 8 a.m. and 6 p.m. Average daily maximum and minimum air temperatures recorded at a weather station located within 19 km (12 miles) of the field test site were 25°C and 9°C, respectively, with a mean daily relative humidity of 59% over the field test duration. No precipitation occurred during the field tests.

A pressure sensor (PX209-100G5V, Omega Engineering Inc, Stamford, Conn.) located on the center pivot swing arm was hydraulically connected such that it measured the pressure at the outlet of the end gun booster pump. When the pump and end gun was on, the measured pressure represented end gun operating pressure and when the pump and end gun was off, the measured pressure represented the pressure in the center pivot swing arm lateral at that location.

RESULTS AND DISCUSSION

Pressure at the outlet of the end gun booster pump logged by the spatially distributed control network as a function of center pivot lateral angular location determined from logged GPS location of the center pivot swing-arm pivot point (tower 9) is shown in figure 2A and 3A for constant and flow proportional injection tests, respectively. Operating status of the end gun is also shown in figure 2A and 3A to aid in interpreting system operation. Comparing figures 2A and 3A revealed that pressure and end gun operation of the center pivot sprinkler irrigation system were very similar for both injection tests. Center pivot irrigation system pressure was slightly lower on occasions during the constant injection test compared to the flow proportional injection test (e.g. 220° angular location). The sprinkler pressure regulator manufacturer recommends a minimum of 21 kPa (3 psi) above the pressure rating of the regulator for proper operation. The end gun pump added approximately 172 kPa (25 psi) to system lateral pressure when it was on. Thus, the minimum pressure for proper system operation was approximately 159 kPa (23 psi) when the end gun was off and 331 kPa (48 psi) with the end gun on. The center pivot lateral traversed the highest field elevations at about 190° to 260° angular location during which the center pivot swing-arm lateral sprinklers were fully on along with the end gun, representing the critical design condition for the center pivot sprinkler system. Examination of measured operating pressure for the constant injection test (fig. 2A) reveals that the center pivot sprinkler system briefly operated at pressures below the minimum

design requirement, with the likely cause being startup of other irrigation systems connected to the same water supply. The consequence of this is that actual flow rate will be less than calculated flow rate based on 138-kPa (20-psi) sprinkler nozzle pressure. Thus, chemical injection proportional to calculated flow rate would be in error, resulting in a greater concentration of applied chemical than desired during this period.

Calculated center pivot irrigation system flow rate is shown in figures 2B and 3B for constant and proportional injection tests, respectively. Calculated flow rate ranged from a high of 4875 L/min (1288 gpm) when the swing-arm lateral sprinklers were fully on along with the end gun to a low of 3330 L/min (880 gpm) when the swing-arm was retracted and the end gun was off, resulting in a flow rate variation of 31.7%. The computed minimum flow is greater than the design minimum flow of 2952 L/min (780 gpm) because two of the sprinkler banks on the center pivot swing-arm were not functioning (turning off as designed). This potential problem was overcome by calculating flow rate of the system as it was operating rather than as designed. The producer was asked to correct the problem but was unsuccessful. Thus, the range in system flow rate shown in figures 2B and 3B is representative of actual field conditions and not actual system design specifications.

Measured dye concentration in the applied irrigation water as a function of center pivot lateral angular location is shown in figures 2B and 3B for the constant and flow proportional chemical injection tests, respectively. With constant chemical injection (fig. 2A), when center pivot sprinkler irrigation system flow rate increased or decreased,

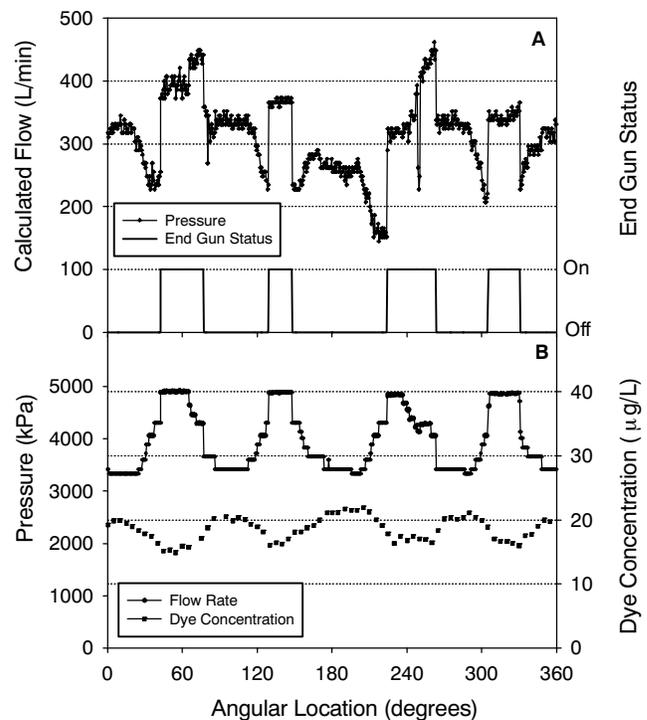


Figure 2. Pressure measured at outlet of end gun booster pump and end gun operating status (A) and calculated flow rate and measured dye concentration (B) as a function of system lateral angular location for constant rate chemical injection.

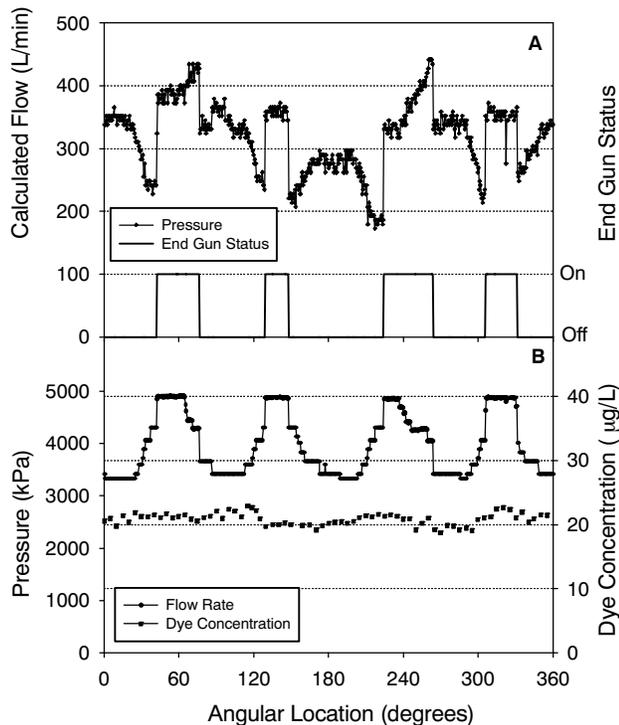


Figure 3. Pressure measured at outlet of end gun booster pump and end gun operating status (A) and calculated flow rate and measured dye concentration (B) as a function of system lateral angular location for flow proportional chemical injection.

measured dye concentration in the applied irrigation water decreased or increased accordingly in inverse proportion. The coefficient of variation in measured dye concentration with constant chemical injection was 0.10. Linear regression analysis of measured dye concentration with calculated center pivot sprinkler system flow rate for constant chemical injection results in an R^2 of 0.74 (fig. 4), thus calculated flow rate accounts for 74% of the variation in measured dye

concentration. The variation in mean measured dye concentration with constant chemical injection over the calculated range in flow rate is 26%. With flow proportional chemical injection (fig. 3B), the mean measured dye concentration in the applied irrigation water varied 2% over the calculated range in center pivot sprinkler irrigation system flow rate. The coefficient of variation in measured dye concentration with flow proportional chemical injection was 0.046, a 54% reduction compared to constant rate chemical injection. Linear regression analysis of measured dye concentration with calculated center pivot sprinkler system flow rate for flow proportional chemical injection results in an R^2 of 0.04 (fig. 4), thus calculated flow rate accounts for only 4% of the variation in measured dye concentration. The small positive regression slope with flow proportional chemical injection is not significantly different ($p < 0.01$) from zero. Thus, the method monitoring center pivot sprinkler irrigation system operating status to calculated flow rate eliminated systematic chemical application errors.

Considerable variation in measured dye concentration is present in figure 4 for both constant and flow proportional chemical injection despite removal of system flow rate variations due to the swing-arm corner watering system and end gun. The variation in measured dye concentration about the regression mean is approximately $\pm 2 \mu\text{g/L}$ and consistent for both chemical injection tests. This variation in measured dye concentration can be the result of several potential sources of measurement error. The primary potential source of measurement error is due to evaporation from the catch cans. When water evaporated from the catch cans during the day, the dye concentration in the water sample increased. Thus, the amount of water evaporated from the catch cans between time of water application and water sample collection will affect the measured dye concentration. Since the water samples were collected an 8 a.m. and 6 p.m., the time for evaporation from the catch cans varied from 0 to 10 hours. For an irrigation application depth of 25 mm (1 in.), a potential evaporation estimate of 6 mm (0.24 in.) would

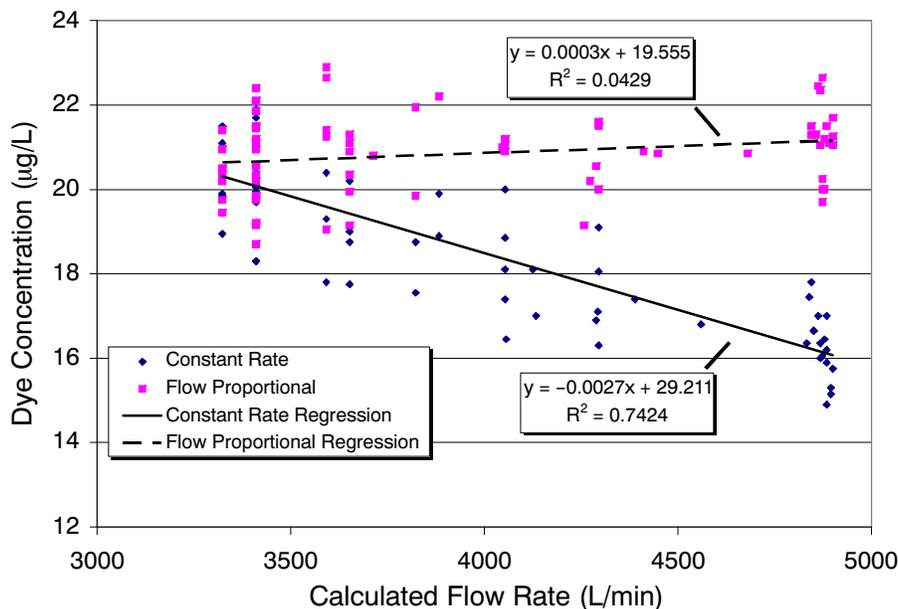


Figure 4. Linear regression equations for measured dye concentration versus computed center pivot flow rate with constant rate and flow proportional chemical injection.

result in a ± 2.1 $\mu\text{g/L}$ potential variation in measured dye concentration.

A second potential source of measurement error is calculation of center pivot sprinkler irrigation system flow rate. System flow rate is calculated based on the assumption that system operating pressure does not affect sprinkler flow rate due to the presence of pressure regulators on each individual sprinkler. The use of pressure regulators does reduce the effect center pivot sprinkler system pressure changes have on sprinkler flow rate but does not completely eliminate the effect. Changes in center pivot sprinkler system operating pressure do affect individual sprinkler flow rates, especially when system pressure is close to the pressure rating of the pressure regulator. Thus, pressure fluctuations due to end gun booster pump operation, elevation changes of the system lateral, and operation of irrigation systems connected to the same water supply along with occurrences of inadequate operating pressure are partially responsible for variations in measured dye concentration under flow proportional chemical injection. Using a center pivot sprinkler flow rate model that accounts for these pressure fluctuations could potentially reduce the effect of system pressure fluctuations on measured dye concentration.

A third potential source of measurement error for the constant rate chemical injection test is the manner in which the water samples were collected. The water samples were not instantaneous grab samples but rather samples collected over the time period required for the sprinkler pattern to completely pass over the catch can. Based on system speed, radial location of catch cans, and wetted diameter of the sprinklers, the collected water samples represent a 30-min average of dye concentration in the applied water. For a specific instantaneous calculated flow rate, the associated measured dye concentration will vary because the water sample corresponds to a range in flow rates over a 30-min period rather than the associated instantaneous flow. The crop canopy could have preferentially interfered with water entering the catch can from one or more directions adding to the variability in measured dye concentration.

Another potential source of error is the effect fluctuations in center pivot sprinkler irrigation system operating pressure have on the flow rate of the chemical injection pump. Kranz et al. (1996) found that chemical injection pump calibration curves change significantly with outlet pressure. Thus, the calibration of the chemical injection pump used in this study may have varied as pressure in the water supply for the center pivot sprinkler irrigation system changed due to operation of irrigation systems supplied by the same water source.

Use of the spatially distributed control network on center pivot irrigation systems provides the ability to monitor, diagnose, and troubleshoot system operation. For example, during field testing it became readily apparent that a producer has limited ability to verify correct operation of the valve banks on a swing-arm corner watering system. Currently, if water is coming out of the sprinklers, the corner watering system is assumed to be working. In our case, monitoring which valve banks were activated and comparing that with visual observations of sprinkler operation, we were able to determine that the swing-arm corner watering system was not operating correctly and identify which valve banks were faulty. The spatially distributed control network also allowed us to monitor operating pressure at the end of the system lateral, which enabled us to determine that operating pressure

was occasionally below design specifications. Currently, there is no easy means to continuously monitor operating pressure at the end of a center pivot sprinkler system lateral and verify proper system operation. We included a GPS unit in the distributed sensor network and logged operational data throughout the irrigation season as a function of time and center pivot sprinkler system lateral location. This information provides a means to determine seasonal water application depth and water application depth per revolution of the center pivot sprinkler based on known system flow rate and actual travel speed. The logged GPS data also allows the travel speed of the center pivot sprinkler system to be evaluated for variations such as wheel slippage or equipment malfunctions. Efficient display and recording of various center pivot operating parameters can be valuable to the producer as a means to ascertain proper operation of the center pivot sprinkler system and diagnose problems when they occur.

The approach used in this study to control flow proportional chemical injection is subject to various sources of failure and error. The main components subject to failure are the spatially distributed control network node electronics, the pressure sensor, and the variable frequency drive. Use of a flow meter for flow proportional chemical injection includes a flow meter, variable speed controller, and variable frequency drive which are subject to failure and error as well. The biggest source of error in flow proportional chemical injection using the spatially distributed control network is in calculation of center pivot sprinkler irrigation system flow rate. Calculation of system flow rate assumes that the center pivot is well designed and operating as designed. Wear and failure of sprinkler pressure regulators, sprinkler nozzle plugging, swing-arm valve controller failure, and swing-arm sprinkler valve failure would all result in errors in calculation of center pivot sprinkler irrigation system flow rate. Overall, the approach used in this study to control flow proportional chemical injection is subject to more modes of failure and error than with use of a flow meter. The magnitude of a flow rate error would depend upon the difference between actual and calculated system flow rate. Failure of a swing-arm valve bank could result in a 5% error in calculated flow rate for the center pivot sprinkler irrigation system used in this study. A 10% drift in pressure transducer calibration could result in less than a 1% error in calculated flow rate for the center pivot sprinkler irrigation system used in this study.

SUMMARY

The feasibility of using spatially distributed control network technology to determine real-time operating status of a center pivot sprinkler irrigation system to calculate system flow rate and control flow proportional chemical injection was evaluated. Field testing results show that this approach to control flow proportional chemical injection system eliminated systematic errors in chemical concentration in applied water caused by center pivot sprinkler system flow rate changes due to end gun and swing-arm operation. Errors in calculation of center pivot irrigation system flow rate could potentially be further reduced by using a center pivot sprinkler flow rate model that accounts for the effect system operating pressure fluctuations have on pressure regulated sprinkler flow rate. The distributed control network

used for real-time center pivot sprinkler irrigation system monitoring is relatively easy to install and provides a means for distributed control and measurement as it uses the existing center pivot power cable for the communication medium. The spatially distributed control network also provides the ability to monitor, diagnose, and troubleshoot center pivot sprinkler system operation.

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