Integrated Decision Support, Sensor Networks, and Adaptive Control for Wireless Site-Specific Adaptive Control for Sprinkler Irrigation

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Abstract. The development of site-specific water management systems for sprinkler irrigation will be a major factor in future efforts to improve the various efficiencies of water use and to support a sustainable irrigated environment. The challenge is to develop fully integrated management systems with supporting elements that accurately and inexpensively sense within-field variability and then optimally control variable-rate water application systems in ways that account for the spatial variability affecting water use. Recent advances in sensor and wireless radio frequency (RF) technologies have enabled the development of distributed in-field sensor-based irrigation systems to support site-specific irrigation management. Thus, integration of a decision-making process with a distributed wireless sensor network (WSN) and providing real-time input to site-specific controls is a viable option. This presentation reviews research on the implementation of in-field micrometeorological information that was fed from a distributed wireless sensor network (WSN) and displayed on a geo-referenced field map in a computer base station. Low-cost Bluetooth wireless RF communications from both a distributed WSN and the machine controls monitoring of sprinkler status and global positioning system (GPS) location were interfaced with a computer base station for processing by a decision support program, which updated the instructions to the variable rate irrigation controller for real-time site-specific control. The decision support was optimized to adapt changes of crop type, irrigation pattern, and field location for instructions for individual sprinkler heads on how much water to apply and where. A graphical user interface (GUI) with a simple click-and-play menu was used, which allowed growers to remotely access field conditions and irrigation status at the home or office via wireless RF communications.


Traditional uniform water applications by self-propelled center pivot and linear move sprinkler irrigation systems ignore within-field variations that cause varying crop yield and quality across most fields. The variability may include topographic relief, changes in soil texture, tillage, fertility, and pests as well as various irrigation system characteristics. These effects on crop production can be additive. Excessive applications potentially lead to drainage, soil erosion, and disease problems as well as excessive energy use, whereas under applications can reduce yields and/or quality with the severity levels often depending on management. Typical management objectives would be to optimize yield and quality while maintaining environmental health (reduced water and agrochemical use) and reduce chemical leaching.

Some modern computerized center pivot control panels enable automatically changing the end tower speed based on a preprogrammed position in the field in as little as 2° increments. This has greatly enhanced the ability of the field manager to apply water to meet spatially variable demand in wedge-shaped segments, but it still assumes an average demand across each wedge-shaped treatment area. Thus, areas of the field continue to be over- or under-irrigated, causing plant stress, reducing yield and quality, and increasing potential for leaching water and chemicals. The next step in the evolution of self-propelled sprinkler irrigation technology is the ability to vary water application along the main lateral of the center pivot or linear move based on position in the field (site-specific irrigation). This capability allows the field manager to address specific soil and/or slope conditions and avoid areas of over- or under-irrigation or, in contrast, to optimally implement managed deficit irrigation and site-specific chemigation strategies.
Advances in communications and microprocessors have greatly enabled the implementation of site-specific water applications by self-propelled center pivot and linear move sprinkler irrigation systems. Site-specific irrigation usually involves some type of variable rate application method in combination with geo-referenced maps or tables (e.g., coordinates of pixels or boundaries) defining “management zones.” These decision maps specify the amount of water to be applied to each predefined management zone within a field and are generated using some type of rule base predetermined by the producer or a consultant. Ideally, these management maps or tables are frequently updated based on real-time, spatially distributed data on field conditions. Management zones may be different for irrigation than for chemigation applications, and each may have its own map.

Microprocessor-controlled center pivot and linear move irrigation systems are also particularly amenable to site-specific management approaches because of their current level of automation and large area coverage with a single lateral pipe. These technologies provide a unique control and sensor platform for economical and effective ways to vary agrochemical and water applications to meet the specific needs of a crop in uniquely defined zones within a field.

Recent innovations in low-voltage sensor and wireless RF technologies combined with advances in Internet technologies offer tremendous opportunities for development and application of real-time management systems for agriculture (Beckwith et al., 2004; Camilli et al., 2007; Liang et al., 2007; Coates and Delwiche, 2008; Kim et al., 2008; Pierce and Elliot, 2008; Vellidis et al., 2008; O'Shaughnessy and Evett, 2008, 2010). Integration of these technologies into the irrigation decision-making process can optimize the use of incident precipitation and determine when, where, and how much water to apply in real time. These types of technologies enable implementation of advanced state of the art water conservation measures for economically viable production with limited water supplies.

One of the basic premises of site-specific precision agriculture (PA) technologies is that crop growth is non-uniform across a field for many reasons and that the requirements for inputs of water and nutrients will also vary. Site-specific irrigation is defined as spatially varying irrigation applications across a field in ways that optimize plant responses for each unit of water. These types of systems have a significant potential to help maximize net returns while conserving substantial amounts of water and energy.

Figure 1 illustrates the concept of self propelled sprinkler systems that apply water at differential rates as the machines move across the field to adjust for temporal and variability in soil and plant conditions. These types of systems are commonly referred to as site-specific variable rate irrigation (SS-VRI). Ideally, weather stations, mobile sensors, and distributed in-field networks of soil, environmental, and/or thermal sensors with wireless communications are integrated into a real-time, automated decision support system to help guide this process.

SS-VRI is generally considered a part of the general group of precision agriculture technologies, which are characterized by site-specific treatments to discrete portions of a field and the use of global positioning systems (GPS). PA technologies include site-specific aspects of planting, fertilizer applications, pest management, and irrigation.

Figure 1. Conceptual system layout of in-field wireless sensor network for site-specific irrigation (Kim et al., 2008).
designed to manage spatial and temporal variability within agricultural fields. Management tools include various types of sensing systems, field sampling, geographic information systems, global positioning systems, wireless communications, on-the-go yield monitoring and decision support systems. However, because of complex spatial and temporal interrelationships, implementation of SS-VRI generally has the most difficult requirements and the most complicated control systems of all PA technologies. SS-VRI is also the most costly in terms of management because of the much higher frequency of treatments compared to other PA technologies.

Various aspects of SS-VRI technology are evolving. For example, several center pivot manufacturers are now promoting the use of automated, electronic soil sensors (e.g., time domain reflectometers, frequency domain reflectometers, capacitance, resistance, etc.) and real-time weather stations that feed back to a database on a central computer at the cart or pivot and a base station. GPS guidance and enhanced, internet-ready computerized control panels are being sold, but few growers utilize these capabilities. Some manufacturers are also selling basic site-specific sprinkler systems as an option, but these generally lack decision support capabilities and means to interface and make irrigation decisions in real time. Some third-party commercial applications are available to assist in defining static management zones and broad irrigation management recommendations, but we are not aware of any commercially available program that integrates all this information and capabilities into some type of a dynamic decision support process for adaptive irrigation management for any type of irrigation system.

In this article, “site-specific” is the preferred term rather than “precision.” Precision irrigation is also used to describe various water application devices as well as the accuracy at which water is uniformly applied across an entire field with microirrigation irrigation systems (Evans et al., 2000). Site-specific is deemed more appropriate because soils and growing conditions across a field are not uniform and a precise, uniform water application may not always be an advantage, particularly when approved agrochemicals are applied. Thus, non-uniform applications (site-specific) may provide an environmental advantage when crop water use is non-uniform, runoff occurs due to topographic or other physical features or when water supplies are limited to less than actual crop evapotranspiration (ET) (Sadler et al., 2000; Sadler et al., 2005; Evans and Sadler, 2008).

Basically, any water application device used on self-propelled sprinkler systems can be utilized for site-specific management of water and agrochemicals applied by the irrigation system. Water application methods commonly used on self-propelled sprinkler irrigation systems are high elevation sprinkler applications (e.g., impact style heads or spray heads) mounted on the top of the main pipe, medium elevation spray application heads (MESA), low elevation spray application heads (LESA) and low energy precision application (LEPA) methods.

Early work on LEPA was directed toward achieving relatively uniform application depths (Lyle and Bordovsky, 1981, 1983). This was later extended to variable-rate, site-specific irrigation situations (Bordovsky and Lascano, 2003). Schneider (2000) reported that LEPA could potentially achieve application efficiencies greater than 95% and that MESA could approach 85% depending on management.

Water and energy conservation needs and environmental objectives may also make it necessary to supersede traditional uniformity criteria with the capacity of the irrigation system to have spatially variable water application capabilities to meet particular site-specific requirements of soils, plant growth, reduced leaching, or other criteria such as an agrochemical application within a field. To achieve such capability, an otherwise conventional irrigation machine would potentially need a variable-rate water application method of some type, a method of position determination (e.g., GPS), and a microprocessor-based device to control water application amounts from each sprinkler head or groups of sprinkler heads based on location and other management criteria. This type of automation for moving sprinkler systems requires the integration of various sensors (on the irrigation machine, on farm equipment and in the field), hardware, GPS, controllers, and computing power (Sadler et al., 2000; Peters and Evett, 2005).

The decision-making process can be enhanced by the use of wireless networks of real-time automated soil water and micro-meteorological sensors or infrared thermometers monitoring of plant temperatures that are strategically distributed to provide continuous feedback to re-calibrate and check various model parameters used in decision support frameworks (Andrade-Sánchez et al., 2007; Kim et al., 2008, 2009; Kim and Evans, 2009; O'Shaughnessy and Evett, 2010). Various sensor systems can also be mounted on the machine and provide real-time feedback for decision support as the machines move across a field (Peters and Evett, 2007, 2008; O'Shaughnessy and Evett, 2010).

By aligning irrigation water applications with variable crop water requirements in the field, it is assumed that total seasonal water use may be reduced thereby decreasing deep percolation and surface run off. Reducing excess water applications will decrease the potential to move nutrients past the plant root zone (King et al., 1995; Sadler et al., 2000, 2005; King et al., 2009), and fungal foliar disease pressure should also decrease.

The design of a suitable site-specific irrigation machine can be complex because of the need to address the causes of the variation, an assessment of the system capabilities needed to achieve the desired management level, constraints inherent in the existing equipment and the philosophy of the owner/operator. These issues are discussed in more detail by Buchleiter et al. (2000), Evans et al. (2000), Sadler et al. (2000), Perry et al. (2004), and McCarthy et al. (2010).

Several innovative technologies have been developed to variably apply irrigation water to meet anticipated whole field management needs in site-specific irrigation, primarily with center pivot and lateral move irrigation systems. In general, the commercial operation criteria for these systems include the following: easy to retrofit to existing center pivots, maintain good water application uniformity within and between treatment areas, robust electronics, compatible
with existing center pivot equipment, bi-directional communication, and expandability for future development and functional requirements. In addition, the management of site-specific water application systems must include physical interactions between individual sprinkler patterns and the start/stop movement of towers.

Objectives of this paper were threefold: 1) review current SS-VRI technology and make some recommendations for the future work; 2) report on the development and field testing of an integrated real time management program for a site-specific linear move sprinkler irrigation system; and 3) to present performance results of the integrated systems. This work started in the 2003 and the system is still being used for irrigated cropping systems research.

SITE-SPECIFIC IRRIGATION SYSTEMS

Maximum application depths on self-propelled center pivots and linear move sprinkler systems are generally controlled by the ground speed of the machine. However, varying travel speed is not a sufficient level of control under site-specific conditions where variable amounts are needed along the length of the machine, and varying output from sprinklers depending on location in the field may be a viable option. Nevertheless, adjusting water application depths just based on soil conditions to fine-tune the water management while considering spatial variability of soils and topography can be a significant challenge.

Site-specific control systems are linked to nozzle hardware assemblies to manage water application amounts. Basically, there have been three approaches implemented for obtaining variable rate irrigation amounts necessary for site-specific sprinkler irrigation. These include the use of multiple sprinkler heads at each outlet to control application depths, adjustable nozzle sizes to control flow rates, and pulse modulation of water application to control depth. Each of these techniques has advantages and disadvantages, and each affects the design of the remainder of the system.

Variations in site-specific irrigation using self-propelled center pivot and linear move systems have been conducted by researchers in several groups to develop site-specific sprinkler irrigation machines. Almost all of this research has been directed toward hardware and software development, and very little has been done to document field-scale water savings or crop-specific management of site-specific machines. Research has been completed in Fort Collins, Colorado (Fraisse et al., 1992; Duke et al., 1992), Aberdeen, Idaho (King et al., 1995; McCann et al., 1997), Prosser, Washington (Evans et al., 1996), Florence, South Carolina (Camp and Sadler, 1994; Camp et al., 2002; Omary et al., 1997), Garden City, Kansas (Klocke et al., 2003), Tifton, Georgia, Clemson, South Carolina (Perry et al., 2003, 2004; Vellidis et al., 2008, Han et al., 2009), and at Sidney, Montana (Evans et al., 2010). Other groups in Europe (Al-Kufaishi et al., 2006) and Brazil (Coelho, R.D., 2009, personal communication) are also investing in various aspects of site-specific irrigation with self-propelled sprinkler irrigation systems.

Several site-specific irrigation systems were installed on commercial farms in south central Washington and on several fields in north central Oregon (Evans and Harting, 1999; Harting, 1999; Harting, G.B., 2004 personal communication). Several of these early studies were summarized in the proceedings of a 2000 ASAE conference (Buchleiter et al., 2000, Evans et al., 2000, Sadler et al., 2000). Site-specific sprinkler irrigation research was also conducted in Georgia on cotton cropping rotations (Perry et al., 2003, 2004; Dukes and Perry, 2006; Vellidis et al., 2008) and on a linear move system in South Carolina (Han et al., 2009). Recent innovative work on site-specific sprinkler irrigation in Washington has also been reported by Andrade-Sánchez et al. (2007) and Chávez et al. (2010a, 2010b, 2010c).

Most of these systems use standard, off-the-shelf equipment with much of the research effort directed toward developing the appropriate control systems. Roth and Gardner (1989) used various sized sprinklers along a lateral move to apply different depths of water as the machine moved. McCann et al. (1997) used either two- or three-boom systems on center pivots which used combinations of two sprinklers sized to deliver a 0, 1/3, and 2/3 or 0, 2/5, and 3/5 of the maximum application rate to achieve a targeted application depth in an area. Omary et al. (1997), Camp et al. (1998), and Sadler et al. (1996) employed a similar approach utilizing combinations of two or three sprinklers applying 0, 1/3, and 2/3 (four steps) or 0, 1/7, 2/7, and 4/7 (eight steps possible) of the maximum application depth. King and Kincaid (1996, 2004) developed an approach based on a needle valve concept where the sizes of the nozzle orifices are modified to achieve different discharge rates on a regular irrigation spray head but it required very precise control and high quality water.

Various investigators have relied on pulse modulation to apply varying depths of water. Pulse modulation is pulsing flow (on and off) of individual or groups of sprinkler heads to achieve a desired depth of application within a specified cycle time (Fraisse et al., 1992; Evans et al., 1996; Duke et al., 1998; Chávez et al., 2010a, 2010b). Cycle time is defined as the sum of total on- and off-times during one-pulse cycle for calculation purposes. For example, an off-time of 12 s out of every 60 s would result in an 80% of maximum application depth. Cycle times can vary depending on the conditions. Evans et al. (1996) used a 250-s total cycle time with rotator heads, whereas Duke et al. (1998), Harting (1999) and Evans et al. (2010) used a 60-s total cycle time with spray heads. Normally-open solenoid valves are typically used to turn sprinklers on and off with pulse modulation methods.

None of the above research developed systems controlled machine ground speed, but only controlled the sprinkler heads. However, there is one commercially available set of controls for site-specific sprinkler that does have the capability to adjust machine speed, which is the Farmscan system (http://farmscan.net.au/default.aspx?ContentID=23), which was also the basic system used in South Carolina and Georgia site-specific irrigation research (Perry et al., 2003, 2004; Dukes and Perry, 2006; Han et al., 2009).
SITE-SPECIFIC CONTROL SYSTEMS

A control system is designed to maintain or alter the operation of a process that is typically comprised of 1) the process being controlled; 2) a sensing system (feedback); and, 3) the hardware and software to control the process. These can be classified into open-loop and closed-loop control systems depending on how the process is managed and adjusted for optimal performance. Open-loop systems are sometimes called feed-forward systems because there is no real-time feedback mechanism to evaluate the quality of outputs or the operation of the system being controlled during operation. For example, most current irrigation decision support programs (often called scientific irrigation scheduling) are basically open-loop systems where irrigation timing and amounts may not equally benefit all areas of a field. Timing and duration of water applications may be based on algorithms predicting irrigation system performance based on historical and predicted climatic and soil water conditions. Open-loop feedback to the process is usually made by point measurements (e.g., soil water) and climate data after the operation is completed and adjustments made for the following irrigation event. Open-loop irrigation control systems can also be simple timers (e.g., preset time on and time off) with little to no feedback. Switching tensiometers that turn on an irrigation based on reaching a set point and run for a set time or until a specified end point. If real-time control is required, most PA technologies utilize open-loop feedback systems (e.g., site-specific spraying).

On the other hand, closed-loop control systems measure the output of a process (feedback, measured response) resulting in periodic adjustments to the controlled parameters during the process in order to minimize the differences between a measured response and the desired response. These types of systems are often referred to as closed-loop or adaptive control systems and have the flexibility to change control parameters to adjust for changing conditions in space and time depending on the feedback mechanisms and limitations (Smith et al., 2009). Closed-loop adaptive control systems are not used with any precision agriculture technology other than site-specific sprinkler irrigation.

Most industrial adaptive control systems typically have at least two feedback loops. The first loop monitors the control variables and compensates for disturbances (noise) or variations in these variables using constant and known parameters or boundary conditions and levels of uncertainty. The second loop (adaptation loop) provides frequent real time feedback on system performance and adjusts and recalibrates control parameters to compensate for disturbances, changing operating conditions and process dynamics to maintain optimal levels of system performance (Landau et al., 1998). Industrial level Supervisory Control and Data Acquisition systems (SCADA) are generally closed-loop adaptive control systems with varying levels of complexity.

The maximum benefits are derived from decision support systems when real-time conditions in selected areas of a field are monitored by various means to improve model simulation output and irrigation scheduling accuracy. Results of geo-referenced grid sampling of soils, yield maps and other aspects of precision (site-specific) agriculture technologies can also be major components of these management systems.

Spatially distributed sensor systems require the seamless integration of the sensing systems, communication systems, and computing technologies. A wireless sensor network (WSN) is preferred because they eliminate difficulties of stretching wire across the field and reduce maintenance costs; however, power requirements of the field wireless systems can be a concern.

SS-VRI RESEARCH

A wide variety of communications protocols, control systems, and computer interfaces have been developed to interact with self-propelled irrigation systems, their chemical injection systems, valves, and sprinklers to implement site-specific management maps for water and agrochemical applications. These have included both open-loop and limited closed-loop control systems. They have ranged from basic SCADA networks (King et al., 1995, 1997, 2000, 2009; McCann et al., 1997; Wall and King, 2004) to less complex systems using programmable logic controllers (PLC) at several locations (Fraisse et al., 1992, Camp and Sadler, 1994, 1997; Sadler et al., 1996; Omary et al., 1997; Camp et al., 1998; Evans and Harting, 1999; Harting 1999; Camp et al., 2002; Perry et al., 2004, O'Shaughnessy and Evett, 2008; Evans et al., 2010), and various types of on-board computers (Evans et al., 1995; Andrade- Sánchez et al., 2007; Chávez et al., 2010a, 2010b, 2010c). Kranz et al. (2010) summarized many of the characteristics of existing site-specific sprinkler irrigation control systems.

Adaptive control of center pivot and linear move sprinkler irrigation systems requires the integration of a decision making process and real time monitoring of field conditions with the irrigation system controls (McCarthy et al., 2010). The specialized software programs that integrate the feedback and other information to develop water application instructions are usually called decision support systems (DSS). DSS for irrigation are intended to utilize holistic approaches to irrigated crop management, which requires the seamless integration of the hardware (physical system), existing control and safety mechanisms, positioning systems (i.e., GPS), software interfacing with predictive crop models and other software tools, field data networks and various types of remotely sensed data, and wireless communications. Most current decision support systems are designed to enhance soil water management approaches to irrigated crop management within a single field or several fields to maximize total yield over the area (Oswald et al., 2005; Thysen and Detlefsen, 2006; Heeren et al., 2007; Kim et al., 2007, Kim and Evans, 2009; Brown et al., 2010; Chávez et al 2010a, 2010b, 2010c).

METHODOLOGY

DEVELOPMENT OF A SITE-SPECIFIC VARIABLE-RATE IRRIGATION SYSTEM

Researchers at the USDA-ARS research laboratory in Sidney, Montana, have developed and tested a variable-rate sprinkler irrigation system, wireless distributed sensor network, and decision support system for automated varia-
ble-rate linear move sprinkler irrigation system. This research integrated the distributed in-field sensor stations, the irrigation control node on the linear move system with a decision support system on a remote base computer station for automatic, closed-loop control of irrigations.

All plots were irrigated with a 244-m, 5-span, self-propelled linear move sprinkler irrigation system (Valmont Industries, Inc., Valley, Nebr.), which was installed in the spring of 2003. Water was supplied by a floating ditch-feed from a level ditch. The irrigation system had six towers including the generator/pump/control cart located at the north end of the system. A diesel engine powered electrical generator set (480 V, 3-phase) on the cart that provided electricity for the tower motors, cart motors, pump, air compressor, and control valves. A buried wire alignment system was used with antennas located in the middle of the machine. Nominal operating pressure was about 250 kPa. Two double direction boom backs were installed at each of the towers (although not at the cart). Spans were 48.8 m in length except for the center span with the guidance system which was a 47.5-m span. The machine moved at about 2.1 m min$^{-1}$ at the 100% setting. The ground speed of the machine established the maximum application depth and treatments were a percentage of maximum by varying on-times in a 60-s cycle time. However, our software allowed us to easily change the cycle time if we needed to make adjustments (Kim and Evans, 2009).

The linear move irrigation system was modified to apply water with two different, side-by-side sprinkler application methods: MESA, and LEPA. When not being used, low-cost pneumatic cylinders lifted the LEPA heads above the MESA heads to avoid spray interference when the MESA was operating over a given plot width and length. A site-specific controller and hardware were developed with the capability to switch between MESA or LEPA methods, as well as to simultaneously vary water application depths by plot as the machine traveled down the field (Evans et al., 2006).

A programmable logic controller (PLC: model S7-226, Siemens, Johnson City, Tenn.) was mounted on a main cart and activated electric solenoids (U8325B1V, ASCO, Florham Park, N.J.) to control 30 banks (15 MESA banks, 15 LEPA banks) of sprinklers via diaphragm valves (Model 205, Bermad Inc., Anaheim, Calif.). The signal interface and software design for the PLC were detailed by Kim et al. (2008).

The machine was converted to make groups of individual sprinkler nozzles electronically controllable by attaching the PLC, solenoids, air valves, and a low-cost WAAS-enabled GPS system (17HVS, Garmin, Olathe, Kans.). The control system was used on fifty-six 15-m $\times$ 24.4-m plots as well as several other smaller research projects in which there were a mix of crops and a prescribed set of management experiments within a single field with a total area of about 12 ha (Evans et al., 2010). Equivalent depths of water were applied by both irrigation methods for the same crop.

Depth of water applied was adjusted by pulse modulation with a 60-s cycle time. Applied depths were based on a digital map stored in the PLC (or in a base computer) for each bank of nozzles as the machine moved down the field. As was the case with most other site-specific controllers in the literature, machine speed was set by the Valley panel and the PLC controller managed the sprinkler heads. Communication signals from the sensor network and PLC irrigation controller to the base station were successfully interfaced using low-cost Bluetooth wireless radio communication. The controller and modifications to the water application methods utilized off-the-shelf components as much as possible.

**DISTRIBUTED SENSOR SYSTEMS AND CONTROL INTEGRATION**

Monitoring systems for SS-VRI require field-based measurements or remotely sensed information or an integrated mix of both types. Remotely sensed data can be local (e.g., mounted on the irrigation machine) or from aircraft and satellites in a variety of formats and resolutions (Peters and Evett, 2007, 2008).

In this research, a distributed WSN was integrated into the management of the existing site-specific linear move sprinkler irrigation system described above. Site-specific irrigation decisions were based on feedback of real-time soil water and environmental conditions from distributed in-field sensor stations. Field conditions were monitored using five in-field sensor stations with dataloggers (CR10, Campbell Scientific, Inc., Logan, Utah) distributed across the field based on a soil property map and monitored soil moisture, soil temperature, and air temperature. The soil water content reflectometers (Model CS616, Campbell Scientific, Inc., Logan, Utah) at the 30-cm and 61-cm soil depths were individually calibrated using a neutron probe. A soil temperature sensor (Model 107, Campbell Scientific Inc., Logan, Utah) was also installed at the 15-cm soil depth and was primarily used to adjust the soil sensors. A nearby weather station measured precipitation, air temperature, relative humidity, wind speed, wind direction, and solar radiation. Sensors at the in-field sensing and weather stations were scanned every 10 s, and data were stored and wirelessly transmitted every 15 min via a Bluetooth radio transmitter (SD202, Initium Co., Korea) back to a base computer. All components at each station are self-powered by a 12-V battery recharged by a solar panel (SX5, Solarax, Sacramento, Calif.). The design for power management and wireless communication for the WSN was detailed by Kim et al. (2006).

The experimental field was configured into five soil zones based on soil electrical conductivity maps. In-field soil water sensors were installed in each zone of the distributed wireless sensor network and remotely monitored by a base station for decision making (Kim and Evans, 2009; Kim et al., 2008, 2009). The soil water sensor readings were stable and closely tracked the rain or irrigation patterns throughout the 2006 and 2007 seasons.

All in-field sensory data were scanned every 10 s and sampled on 15-min intervals. Communication signals from the sensor network, weather station, and PLC irrigation controller to the base station were successfully interfaced.
using low-cost Bluetooth wireless radio communication. The design for power management and wireless communication for the WSN was detailed by Kim et al. (2008).

**Decision Support System**

Control software was designed to provide real-time monitoring and control of both inputs (field data) and outputs (sprinkler controls) by a simple click-and-play menu using graphical user interface (GUI), and optimized to adapt changes of crop design, irrigation pattern, and field location. This software provided remote access to the distributed WSN and variable rate irrigation control system. In-field micrometeorological information was displayed on a geo-referenced field map in a base computer station. Figure 2 illustrates the decision-making process used in this research.

The PLC on the machine provided the current geo-referenced location of the linear move machine from an on-board differential GPS at the cart. The base computer recalculated the position of individual sprinkler heads, analyzed sensor data, updated control signals on water amounts, and sent control commands to the irrigation control station to site-specifically operate each individual sprinkler group to apply a specified depth of water for every time step (1 s) based on criteria in a predetermined management map.

The decision-making program integrated the irrigation system hydraulic data, location of each sprinkler bank, directed the site-specific water application depths and whether MESA or LEPA methods would be used. The software tracked GPS locations of the irrigation cart and sent individual control signals to the 30 sets of sprinkler nozzle banks every second either automatically or manually on request.

Irrigation depths were based on calculations of the amount need to meet the difference between the midpoint of the readings from the two soil water sensors in each WSN zone and a preset upper soil water limit within the time constraints of machine travel speed. The upper soil water content limit was slightly less than estimated field capacity to leave room for incident precipitation. Actual water application depths for the MESA and LEPA heads utilized pulse modulation based on the calculated percentage of a 60-s valve duty cycle.

**Evaluation and Performance**

User-friendly software was developed to interface the base station with a PLC irrigation controller and wireless in-field sensor network for GUI-based real-time irrigation control and monitoring. The irrigation sprinklers successfully followed real-time wireless control signals throughout the irrigation operation without interruptions in wireless radio communication. About a 1-s signal lag was observed between the base computer and the PLC due to the wireless communication. Additional time lags up to 3 s was observed in nozzle activation due to the hydraulic power transition. These time lags were not degrading irrigation performance, since the irrigation machine moved at a maximum of 3.5 cm s⁻¹. The signal range between two Bluetooth radio modules used in this research was up to 1200 m in line of sight and could be extended by a repeater. Seamless wireless communication was obtained throughout the 2007 and following growing seasons.

An algorithm for nozzle sequencing was also developed as part of the decision support software to stagger nozzle on-off operations so as to evenly distribute irrigation system flow rates over the 60-s cycle to avoid hydraulic surges and pressure fluctuations that could cause system damage. This behavior was evident when all nozzles were turned on at the beginning of a cycle or when several valves were switched off at the same time in the middle of a duty cycle. Therefore, an algorithm for nozzle sequencing was developed and added into the decision support process to stagger nozzle-on operations so as to improve the distribution of irrigation system flow rates and pressures over the entire

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**Figure 2. Schematic of the decision-making process for the SS-VRI system (Kim and Evans, 2009).**
60-s duty cycle. As an example, Figure 3 shows the flow rates and the status of each sprinkler bank during one duty cycle. The horizontal bars on the right side of this two-part graph shows the on-times of all sprinkler banks to deliver the required application depths, whereas the bars on the left indicate the times the valves were turned on and off for each sprinkler bank that resulted from staggering algorithm. The upper portions of the graphs show the flows throughout the cycle with and without staggering on and off times.

For the performance evaluation of wireless control of the SS-VRI system, five sets of catch can tests were conducted on the MESA heads to determine the accuracy of meeting targeted application depths of either 10 or 25 mm. Different blocks of heads (15-m width) were programmed for 25%, 50%, 75%, and 100% of the targeted amount. The linear move irrigation machine was then moved through the can sites and the data manually recorded. LEPA head tests did not use catch cans, but were individually measured with buckets and a stop watch to calculate the applied volumes for the various programmed depths. Weather data (e.g., wind speed and temperature) were recorded at an automated agricultural weather station at the edge of the field. Targeted variable rate irrigation depths were highly correlated to catch can water results with \( r^2 = 0.98 \) (Kim and Evans, 2009).

A control panel dialog was created to configure data interface for the irrigation control system. The GPS clock was corrected from Greenwich Mean Time (GMT) to a local time based on a time zone, and -6 was added to represent U.S. Mountain time with daylight saving. The GPS offset was set to zero for both x (east) and y (north) axes, as the GPS was mounted on the middle of a main linear control cart with sprinkler nozzles aligned along a longitude line. The status of communication ports for the GPS and PLC were automatically detected on the software initiation, and corresponding serial port numbers were displayed. A pushbutton 'Irrigation Control' opened a real-time GPS-based irrigation control and monitoring dialog. During the irrigation operation, PLC communication connectivity was alerted every second after a complete cycle of data processing by a short beep sound, ranging from 0 (silent) to 10 (loudest).

The 15-min update rate of the WSN data was based on a computer clock, while 60-s duty cycle of irrigation operation was based on a GPS clock. To avoid time mismatch between sensor feedback input and irrigation control output data in decision making, it was necessary to synchronize a computer clock with a GPS clock and convert to a correct local time by clicking a pushbutton of 'Synch PC clock with the GPS'. All data were recorded during the irrigation operation and saved to a file named ‘PLC_mmdd.csv,’ where ‘PLC’ was a default filename and ‘mm’ and ‘dd’ were the current month and day, respectively. Each data string contained actual amount of water applied on each plot with GPS data.

A similar wireless irrigation system for linear move sprinkler systems was introduced by Han et al. (2009) and evaluated for SS-VRI. They showed results of a static nozzle test and a uniform test. However, their system was neither integrated with a decision-making process nor tested with in-field sensor feedback. Seamless integration of the irrigation system with accurate field sensing from in-field WSN is a key technology to achieve a fully automated efficient management of SS-VRI.

The sensors and hardware developed in this research are designed mobile and relocatable, and thus their applications can be extended to other types of irrigation systems and management such as deficit irrigation in orchards. Software must be also optimized to overcome constraints such as seasonal changes of irrigation patterns and different irrigation machines at different locations. Thus, software developed in this research was designed to adapt to changes of crop layout, irrigation pattern, plot scale, and field location.

**CONCLUSIONS**

A site-specific irrigation system has been designed, installed, and successfully tested on a self-propelled linear move sprinkler system. The PLC-based control system has worked well over a 5-year period (2004-2008). The system successfully switched between MESA and LEPA irrigation methods as it moved down the field. This equipment greatly increased our research flexibility and allowed researchers to address multiple experiments under the same linear move system, greatly maximizing results and utility of these expensive machines.

Implementing automated site-specific irrigation is challenging in system integration and decision making. This research showed that irrigation decisions can be implemented site specifically based on feedback from soil water

![Figure 3. Screen capture of the effect of the sprinkler on-off time staggering algorithm for a 60-s duty cycle (MESA in black and LEPA in gray, white indicates not on).](image-url)
and environmental conditions from distributed in-field sensor stations using wireless RF communications.

This project illustrates it is possible to effectively install and operate precision site-specific irrigation systems on self-propelled linear move and center pivot systems. The knowledge of soil variability within a field is fundamental to the development of site-specific management areas since different soils have different water holding capacities. The ability to vary water application along the main lateral of the linear move based on position in the field allows researchers as well as producers to address specific soil, crop and/or special research conditions/treatments.

By aligning irrigation water applications with variable water requirements in the field, it is assumed that total water use may be reduced thereby decreasing deep percolation and surface run off. Reducing excess water applications will decrease the potential to move nutrients past the plant root zone and fungal disease pressure should also decrease. Integration of the decision making process with the controls is a viable option for determining when and where to irrigate, and how much water to apply. Distributed in-field sensors offer a major advantage in supporting site-specific irrigation management that allows producers to maximize water productivity while enhancing net profitability.

Site-specific irrigation decisions should be based on feedback of real-time soil water and environmental conditions from distributed in-field sensor stations. Optimal use of available precipitation will obviously be required. The maximum benefits will be derived from a decision support system when soil water levels in selected areas of a field are monitored by some means to improve model simulation output and irrigation scheduling accuracy. Results of georeferenced grid sampling of soils, yield maps and other aspects of precision agriculture technologies can also be major components of these management systems. Monitoring systems can be field based measurements or remotely sensed or an integrated mix of both types.

Remote, real-time monitoring and/or control of important farming operations that add value through improved efficiency and efficacy of targeted, site-specific management practices (precision agriculture) are now available, but are not generally being applied for a number of reasons. The development and field testing of the real-time irrigation management program reported in this manuscript has shown that integration of the specific irrigation system, wireless in-field sensor networks and decision support for site-specific sprinkler systems is a viable option for both research and commercial applications.

This research showed that site-specific irrigation decisions can be based on feedback of real-time soil water and environmental conditions from distributed in-field sensor stations. Integration of the decision-making process with distributed sensor systems for real-time control is a viable option for determining when and where to irrigate, and how much water to apply. Distributed in-field sensors offer a major advantage in supporting site-specific irrigation management that potentially allows producers to maximize water productivity while enhancing net profitability. Monitoring systems can be field-based measurements or remotely sensed or an integrated mix of both types. While this technology was developed on a linear move irrigation system, it was designed to also work with center pivots.

There is little question that site-specific sprinkler irrigation systems like the one described in this manuscript are wonderful research tools. However, almost all of the research done to date has been directed toward development and improvement of hardware and control software. Little research has been done on the management of these systems for greatest agronomic benefit, and that has been directed toward meeting full crop ET and maximizing yields per unit area.

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