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Automated Support Tool for Variable Rate Irrigation Prescriptions

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Abstract. *Variable rate irrigation (VRI) enables center pivot management to better meet non-uniform water and fertility needs. This is accomplished through correctly matching system water application with spatial and temporal variability within the field. A computer program was modified to accommodate GIS data layers of grid-based field soil texture properties and fertility needs in making management decisions. The program can automatically develop a variable rate application prescription along the lateral for the entire field based on soil texture, slope, water, and crop chemigation needs, with the goal to improve production while making better use of water and fertilizer. Prescriptions could be developed for VRI using individual sprinkler control, defined sprinkler zones, or system rotation speed changes. Results are presented for a specific field showing: 1) automatic determination of the maximum application depth based on each respective application rate along the lateral matched to the soil intake rate at each position; and 2) the corresponding prescription maps for variable rate chemigation for three types of VRI control. The program outputs management prescriptions in both text format and graphically to enable growers to visually assess the results. Future work will be directed at converting management prescriptions into a format directly usable by pivot control panels.*

Keywords. *Center pivot, chemigation, fertility, prescription, Variable Rate Irrigation (VRI)*

Introduction

Irrigation systems have been traditionally designed to apply water as uniformly as possible. However, non-uniform field combinations of soil texture, topography, and fertility levels give justification for providing a means to apply water variably across a field. Center-pivot irrigation offers control flexibility to accommodate various management options, especially with variable rate irrigation (VRI) technology, to manage water application spatially and temporally. Growers typically want to ensure the entire crop receives the minimum depth of water to meet crop water requirements, which is why they often over apply water depth at some field locations. This is particularly true for non-uniform fields. There is a need to develop fully integrated management systems that accurately and inexpensively define dynamic management zones, sense within-field variability in real time, and control variable rate water application adaptively (Sadler et al., 2005). The design selection of irrigation depths, nozzle diameters along the pivot lateral, and pivot length in relation to the soil type may be more relevant than the selection of the sprinkler type itself (Playán et al., 2004). Valín et al. (2012) concluded that suitable design and management of center pivot irrigation with soil infiltration characteristics is a very useful tool to prevent runoff. Improved water management practices may also reduce the impact of irrigated production on offsite water quantity and quality.

Simulation models of water distribution from center pivot systems, including CPED (Heermann and Hein, 1968), USUPIVOT (Allen 1989), and CPIM (Evans et al., 1993), have been developed to support design and improve irrigation systems. Some models have been developed for estimation of runoff and soil loss or field evaluation of system operation using distribution uniformity and the uniformity coefficient, such as Silva (2006), López-Mata et al. (2010), and Duke and Perry (2006). Valín et al. (2012) developed the DEPIVOT model that uses field data and farmers' needs to design changes in existing systems, such as selection of a sprinkler package, and evaluate the relevant runoff potential. Martin et al. (2012) presented updates to models for computing runoff potential based on characteristics of sprinkler devices and soil textural classes using a dimensionless solution to the Green-Ampt infiltration method. They concluded that system design and irrigation management are two required factors to assess the runoff potential. Their model, which combined runoff and evaporative loss estimates, allows comparing of tradeoffs in sprinkler package selection.

Models relating potential runoff to sprinkler peak application rate have been developed by Dillion et al. (1972), Slack (1980), Gilley (1984), DeBoer et al. (1988), Allen (1990), Wilmes et al. (1993) and Martin et al. (2012). Gilley (1984) determined the maximum application depth without causing runoff by combining the effect of water application rate and SCS Soil Intake Family curves. Based on the work of Gilley (1984), von Bernuth and Gilley (1985) developed a methodology for estimating center pivot sprinkler irrigation runoff which considered infiltration rate reduction due to water drop impact on bare soil.

Nguyen et al. (2015) developed a computer model to accommodate GIS data layers of grid-based field soil texture properties to support improved management decisions with center pivots. The program can develop variable application prescription rates along the lateral for the entire field based on soil texture, slope, irrigation system characteristics, and required irrigation depth.. The model could be used on VRI systems with individual sprinkler control, defined sprinkler zones, or system rotation speed changes. Results for a specific field indicated that all three methods of VRI management resulted in reduced potential runoff, and that individual sprinkler and zone control provided the best reduction.

Chemigation is the application of agricultural fertilizers, soil amendments and pesticides through irrigation water. Pivots can provide precise, uniform water application to field crops. When chemigation is done through pivots, those same advantages are still achievable, while improving the quality and quantity of crops. Sayed and Bedaiwy (2011) conducted a two-year experiment in the desert west of the Nile Delta to study the effect of chemigation on wheat grain yield. Their results showed an improvement in wheat grain yield, which was attributed to the more uniform distribution of added nutrients (nitrogen and potassium) in the root zone under the chemigation treatment in comparison with the traditional application method. Concentrations under traditional application resulted in lower levels in the upper soil and greater levels deeper in the root zone, exceeding safe limits and subjecting the soil and groundwater to contamination hazards. For both N and K fertilizers, fertilizer use efficiency was greater under chemigation than under traditional application. Efficiencies increased with increasing irrigation water, apparently due to better fertilizer distribution. Applying herbicides with sprinkler irrigation water reduced weed infestation from 48% to 6.5%. As a result of improved yield under chemigation, an increase in revenue per hectare of 112.6% was achieved.

Chemigation has been found useful in reducing pathogenic fusarium wilt (Ozbahce 2014). Vieira and Sumner (1999) determined that white mold (Sclerotinia sclerotiorum) rates decreased through chemigation of fungicides n dry beans. Fungicides applied by sprinkler irrigation reduced the severity of Rhizoctonia crown rot of sugar beets (Potter and Schneider 1981) and reduced the severity of white mold on peanuts (Sumner and Littrell 1989) and dry beans (Vieira et al. 2003). Other research results on fungicide residues remaining in the soil were less with chemigation than with ground application (Brennman et al. 1990; Ozbahce 2014).

The overall goal of this research is to improve production while making better use of water and fertilizer. The objective of this specific study was to modify the model of Nguyen et al. (2015) to automatically define maximum application depth without runoff along a center pivot lateral for SCS Soil Intake Families, and to add the capability to develop chemigation prescriptions for center pivots using VRI management.

Methods and Procedures

The computer program developed by Nguyen et al. (2015) (in Visual Basic, Visual Studio software, Microsoft Corporation, Redmond, WA) constructs irrigation prescriptions and representative field maps for center pivot VRI management in fields with non-uniform soils. The program is based on geometric relationships which represent the smallest unique management area of application depth for a given angle of movement of a center pivot. Management zones are defined in both the axial position along the lateral and the azimuth angle for the respective sprinkler or VRI zone. The minimum land area that can be defined as a unique zone is related to the wetted diameter and sprinkler spacing, and the angle or pivot rotation needed to only apply water in that area. The GIS based data are input in raster format as a spatial data structure that defines space as an array of equally sized cells arranged in rows and columns. From the GIS grid with defined cell size, the program converts the grid-based raster data into polar-based data at every sprinkler along the pivot for every one degree azimuth angle in the field. The Z-value at every sprinkler location throughout the field is estimated using bilinear interpolation. The program can develop application prescription maps to optimize irrigation to meet crop water requirements without runoff at all points along the lateral for all positions in the field.

In this study, the method developed by Gilley (1984) was used to determine the maximum application depth possible without runoff based on sprinkler peak application rate, surface water storage (function of field slope), and the respective SCS Soil Intake Family. The Nguyen et al. (2015) program assumed that the greatest potential for runoff occurred at the distal end of the lateral since the greatest application rate coincides with the largest area irrigated by a given sprinkler. However, for fields with non-uniform soil characteristics, the limiting position for maximum application depth without runoff, may occur closer to the pivot where the application rate is less than at the end of the lateral (for example, a clay soil near the pivot point with a coarser soil near the distal end). In that case, it is necessary to evaluate the limiting application rate along the entire lateral, as is done in this study.

To automatically determine the maximum application depth for SCS Soil Intake Families as a function of application rate, a separate program was developed following the method of Gilley (1984) using the equations for elliptical application rate specified by Kincaid et al. (1969). This eliminated the previous need to manually read the Gilley (1984) curves for the respective SCS Soil Intake Families.

The Nguyen et al. (2015) program was also modified to develop VRI chemigation prescriptions for center pivots. An important aspect for chemigation or fertigation is in calculating the injection rate of the fertilizer or chemical. Traditionally, the amount of chemical applied to a field is based on a fixed chemical concentration in the water times the respective total water volume applied. This works well for fields that have uniform needs. For non-uniform fields or fields that would benefit from site-specific chemical application, the ability to vary the chemical application depth throughout the field can improve chemical use efficiency while reducing the potential for off-site pollution. The data needed to develop prescriptions can be from site maps, such as through remote sensing, identifying requirements throughout the field. The amount of chemical applied can then be varied by changing the pulse rate of sprinklers for VRI sprinkler and zonal control, or by changing the pivot speed of rotation for sector control.

For this study, the VRI field performance was based on a Valley 8000* system located at the University of Missouri T.E. Fisher Delta Research Center in Portageville, MO. This is a 152 m long, three tower system divided into ten unique sprinkler zones. This system is equipped with Senninger fixed spray nozzles spaced 2.3 m apart (65 total sprinklers) with no end gun. Average flow rate at 100 percent sprinkler capacity is 1893 L/min. Sprinkler wetted diameter varies from 9.8 to 11.6 m. Minimum rotation time at 100 percent rotation speed is 3.3 h and the system can apply over 37 mm in a 24-hr period. Additional system characteristics can be found in Nguyen et al. (2015).

A VRI schedule can be developed to eliminate potential runoff by matching the maximum application depth without runoff for a given soil texture. The particular field used in this study included five different soil series with three different soil textures (*Dundee silt loam, Tiptonville silt loam, Reelfoot loam, Steele sandy loam, and Reelfoot sandy loam*) (http://websoilsurvey.sc.egov.usda.gov) (Figure 1). Soil type in the field was classified based on the percentage of sand content matched to NRCS soil survey maps for the given area (Table 1). Sand content was estimated using a Veris 3100 unit to determine the soil electrical conductivity (EC_a) for two depths (0 to 30 cm and 0 to 90 cm). Data were collected on a 1-s interval on N-S transects spaced 10 m apart, resulting in a 4 to 6 m spacing. These data were then kriged to a 3 m x 3 m grid. Twelve soil cores to a depth of 76 cm were collected across the field, and used to calibrate EC_a to profile sand content. Sand percentage in 10 percent increments is shown in Figure 2. For input to the program, soil texture grid data were directly read as input from a text file. The data were represented as 3 m x 3 m cell size in the WGS84 UTM Zone 16N coordinate system. The file includes lines of X, Y, and Z, where X and Y are Easting and Northing, respectively, and Z represents the sand percentage of soil.

Table 1. Soil information in pivot field area, T.E. Fisher Delta Research Center, University of Missouri, Portageville, MO

Map Unit Symbol	Soil Series	Percent Sand (surface to 0.18 m)	SCS Intake Family
82077	Dundee silt loam	14.8	0.1
82085	Tiptonville silt loam	21.4	0.1
86043	Reelfoot loam	49.2	0.3
86065	Steele sandy loam	66.6	0.5

86044	Reelfoot sandy loam	77.3	1

Figure 1. Soil map (from soil survey – NRCS) http://websoilsurvey.sc.egov.usda.gov.

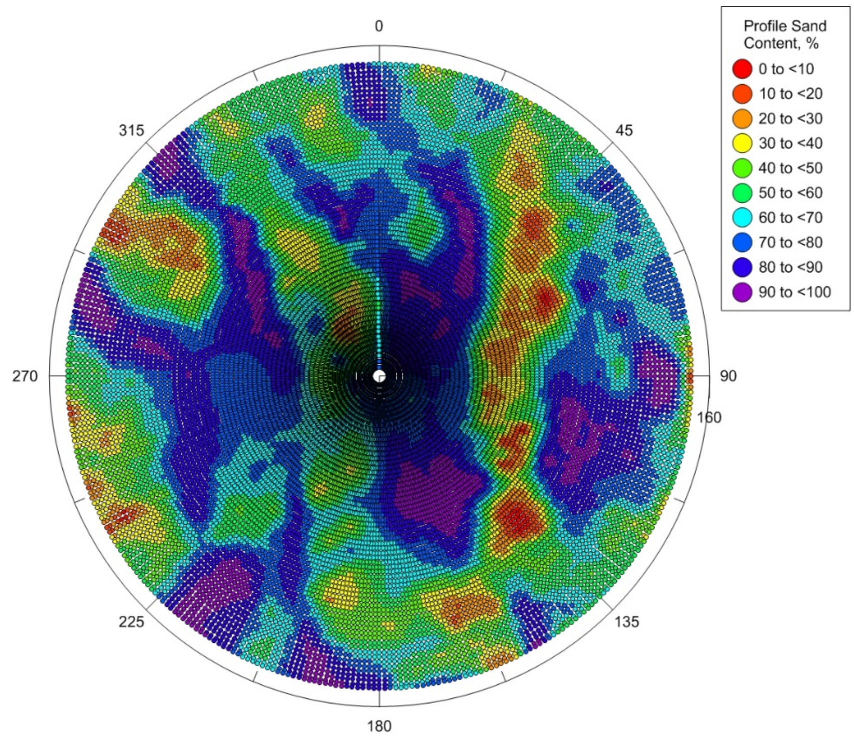

Figure 2. Profile sand content as measured for center pivot field area.

Results and Discussion

Simulations were run for each of the VRI scenarios and for a system with no VRI. Results are presented based on potential runoff for single irrigation cycles and for seasonal totals. Color maps representing the soil texture and resulting VRI management are included to gain a better understanding of differences among the different management methods.

Figure 3 was developed to illustrate use of the Gilley (1984) method for determining maximum application depth for a given application rate for several SCS Soil Intake Families. (Note that the computer program will do this automatically.) In this figure, the relationship between peak application rate and the maximum amount of water that can be applied per irrigation is shown assuming 7.6 mm surface storage. For example, using the center pivot at the Fisher Delta Center, at 70^o azimuth the peak application rate at the end of the pivot lateral is 165 mm h^{-1} and it is operating over a 1.0 SCS Soil Intake Family (Reelfoot sandy loam - sand percent greater than 75%). Using Figure 3, the corresponding maximum irrigation depth without runoff is 25 mm. At this same azimuth position at a distance of 36 m from the pivot, the application rate is only 50 mm h^{-1}, but that position of sprinklers is directly above a 0.1 SCS Soil Intake Family (Tiptonville silt loam). The maximum application depth without runoff here would be 15 mm. Therefore, the greatest potential for runoff is at a point only 24% of the distance along the lateral rather than at the end of the machine. The irrigation prescription using the revised program automatically accounts for this, adjusting the pulse rate of sprinklers along the lateral, to avoid runoff during irrigation to meet crop water requirements.

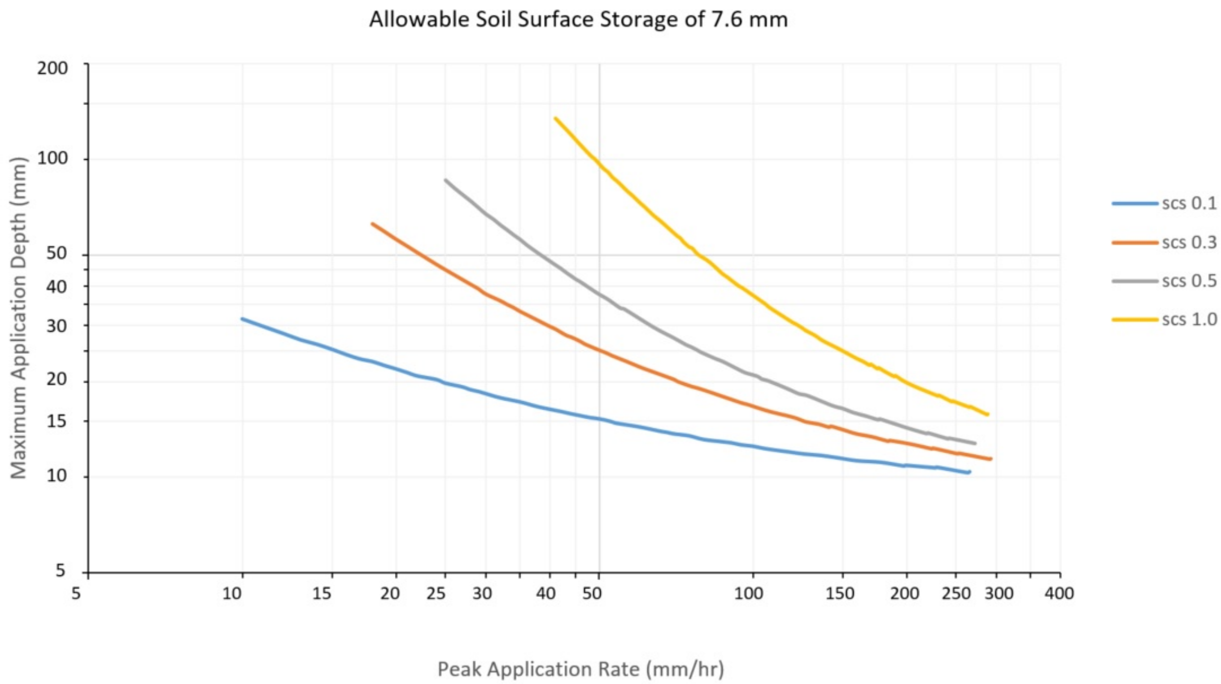

Figure 3. Maximum depth of water application per irrigation for 7.6 mm surface storage.

A chemigation prescription map can be similarly developed based on unique fertility needs throughout the field. To demonstrate the chemigation analysis of the program, a uniform fertility prescription was developed for a corn crop. The example is based on an assumed N-application of 45 kg ha^{-1} for the field at Portageville. It is typically recommended that N-fertilizer be applied with 12 to 25 mm of water per application (https://www.midwestlabs.com/wp-content/uploads/2013/08/foliar_nutrition.pdf). For this example, a design depth of 19 mm of irrigation water was scheduled to apply the urea fertilizer, which required a machine rotation speed of 26% (rotation time of 12.7 hours). Fertilizer concentration was based on a urea solution containing 0.26 kg N L^{-1}. The chemical injection rate was determined to be 0.14 m^3 h^{-1}, which required a total volume of 1.8 m^3 urea solution for the entire field. Variable fertility requirement was identified using remotely sensed GIS data represented by 3 m x 3 m cell sizes of crop fertility needs. From these GIS data, field areas were identified that required up to 65 kg ha^{-1}, which is more than 44% greater than the design amount of 45 kg ha^{-1}. Therefore, using the maximum N-application for this combination of soil and crop, 65 kg-N ha^{-1} was applied using a VRI sprinkler pulse rate of 100% and 45 kg-N ha^{-1}.was applied using a pulse rate of 70%. The program was then used to develop fertilizer prescriptions for the field using VRI methods of sprinkler control and zonal control for pulse rates between 70 and 100% in 5% increments, the smallest pulse rate adjustment for the pivot VRI 6.5 version software. A VRI prescription for sector control was also developed to vary rotation speed in 1% increments since sprinkler pulsing is not available on all machines. Note that real time control and monitoring of the center pivot irrigation system would be needed to keep chemical injection rate proportional to the center pivot flow rate to maintain constant chemical concentration in the irrigation water.

Figure 4a shows the fertility treatment areas based on VRI Single Sprinkler control. The advantage of this method is that groups of sprinklers that make up a unique application area can be varied in number and location along the lateral to accommodate the required variations in concentration of chemical, both along the lateral and in the direction of travel. Note that the resolution of fertigation application is limited only by the sprinkler wetted diameters and respective overlap of adjoining sprinklers.

The treatment areas based on using VRI Zonal control are shown in Figure 4b. These are based on the ten sprinkler control zones of the Valley 8000 system used in this field. Because these zones are fixed in position along the lateral, the ability to match specific variations is not as precise as for single sprinkler control, but the overall pattern is similar to that for individual sprinkler control.

The chemigation prescription map for VRI Sector control where all sprinklers are operated at 100%, is shown in Figure 4c. Although the ability to match smaller variable fertility needs is reduced, the advantage of this VRI management scheme is that it can be readily adapted to existing center pivots with existing chemigation injection systems since there is no need for a variable frequency chemigation pump to maintain constant chemical concentration. The machine is simply run slower in areas that require more fertilizer. The minimum amount of chemical needed will be applied when the system is operated at maximum speed. To take advantage of VRI sprinkler or zonal control for fertigation requires a variable rate chemical injection pump matched to the variable frequency drive (VFD) adjusting the water pumping rate as the sprinklers or zones are being pulsed on and off, maintaining a constant chemical concentration in the irrigation water.

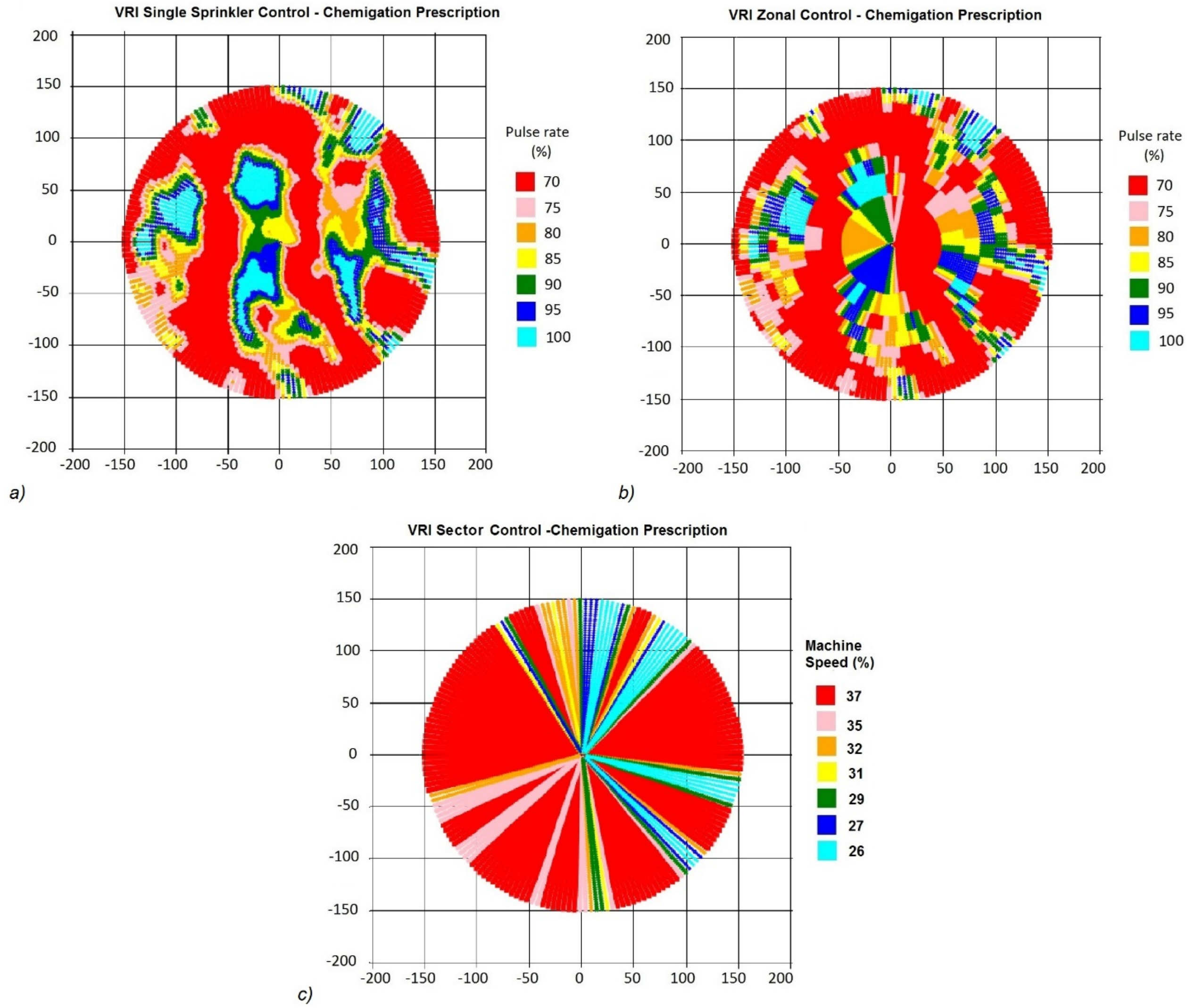

Figure 4. Chemigation prescriptions: a) Chemigation prescription for VRI Single Sprinkler control program output ; b) Chemigation prescription for VRI Zone cntrol program output ; c) Chemigation prescription for VRI Speed control program output.

Conclusion

The objective of this study was to modify the Nguyen et al. (2015) program to automatically determine maximum application depth without runoff along a center pivot lateral for SCS Soil Intake Families, and to expand the model to develop chemigation prescriptions for VRI systems. Results from design examples for this study were completed using the center pivot irrigated field at the T.E. Fisher Delta Research Center. In this new version of the program, the user is no longer required to manually lookup SCS Soil Intake Family curves, nor is the limiting peak application rate required to be at the distal end of the lateral.

Chemigation prescriptions were developed to accommodate GIS data layers as a management decision tool to improve water management and match chemical need. The program outputs management prescriptions in both text format and graphically to enable growers to visually assess the results. Further development is needed to convert prescriptions into a format directly usable by pivot control panels.

*Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement.

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