ENGINEERING APPLICATIONS OF SOIL INFORMATION SYSTEM (SIS): PRECISION IRRIGATION AND DRAINAGE SYSTEMS DESIGN

A Record of Study

by

BILGE KAGAN CEYLAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF ENGINEERING

May 2008

Major Subject: Engineering
College of Engineering

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Approved by:

Chair of Committee,	David N. Ford
Committee Members,	Stuart Anderson
	Ken Reinschmidt
	Don Smith
	Nick Guries
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ABSTRACT

Engineering Applications of Soil Information System (SIS): Precision Irrigation and Drainage Systems Design. (May 2008)

Bilge Kagan Ceylan, B.S., Middle East Technical University;
M.S., Texas A&M University
Chair of Advisory Committee: Dr. David N. Ford

The objectives of this internship were to demonstrate and apply the knowledge and technical training obtained during Doctor of Engineering coursework and to become familiar with the organizational approach to problems. These objectives were fulfilled in three commercial research and development projects in the field of precision agriculture. The first project involved optimization of a center pivot irrigation system in coordination with the system's manufacturing company in order to apply irrigation water to maintain uniform soil water content across the field. An optimization-simulation model was developed for this purpose using a dynamic programming approach. The simulations run by the optimization model showed that the existing pivot speed prescription resulted in a more uniform soil water content across the field reducing the crop yield losses. The objective of the second internship project was to analyze the agricultural drainage industry for identification of the potential applications of the spatial soil information into agricultural drainage design and construction. In order to accomplish this task, a comprehensive literature survey was conducted with an emphasis on the drainage approximate equation and numerical methods. Software tools that are currently employed in drainage design and construction were evaluated. A detailed market analysis was conducted with a focus on the industry stakeholders. A strategic strengths, weaknesses, opportunities and threats (SWOT) analysis was conducted for the agricultural drainage industry using Porter's five forces method. The last internship project involved investigation of the potential for using soil information obtained by SIS in the assessment of soil salinity. A correlation analysis was conducted between the soil paste extract electrical conductivity values measured in the laboratory on collected soil samples and those estimated using the soil resistivity values collected by the SIS, which is a measure of soil salinity. The results showed no clear correlations. While the internship projects provided the intern the opportunity to apply some of the analytical methods learned as part of the Doctor of Engineering coursework, they also provided invaluable experience for the intern to understand research and development projects in a business environment, which was one of the major objectives of the internship.

DEDICATION

Dedicated to my mother and father, Raziye Ceylan Cimen and Aydemir Ceylan, who taught me the value of education and knowledge and supported me throughout this long effort. Also dedicated to my wife, Anna Vigdorchik, for her never-ending support and patience throughout this challenging period of our life and to our son, Deniz Kagan Ceylan, for his inspiration in everything we do.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. David N. Ford, and my committee members, Dr. Anderson, Dr. Reinschmidt, Dr. Smith, and Nick Guries, for their guidance and support throughout the course of this research. I also would like to thank Dan J. “The Tavla Master” Rooney, president of Soil & Topography Information, LLC for the great opportunity to conduct my internship in STI and gain invaluable experience, as well as all other assistance and support whenever necessary for successful completion of this study.

Thanks, once again, to my mother, Raziye Ceylan Cimen, and father, Aydemir Ceylan, whose inspiration was the main motivation for me to start and complete this study. I also would like to thank to my brother, Gultekin Ceylan. Thanks also go to my wife, Anna Vigdorchik, for her never-ending patience and love and, the last but not the least, my son, Deniz K. Ceylan for the joy he brought to our lives during the second half of this study. I also would like to extend my gratitude to my mother-in-law and father-in-law, Asia and Anatoly Vigdorchik. Anatoly Vigdorchik’s encouragement was a big support for this study. His memory will always be with us. I also would like to thank to Zerrin Ceylan.

Finally, I would like to thank Yavuz M. Corapcioglu for his valuable guidance and support in all matters throughout this study and the motivation and support he provided for my M.S. as my graduate advisor, which made this degree possible in the first place.

NOMENCLATURE

CP	Center pivot
CYL	Crop yield loss
E	Evaporation
EC_a	Apparent electrical conductivity
EC_e	Saturated soil paste extract electrical conductivity
EC_s	Electrical conductivity of the indurated soil phase
EC_w	Electrical conductivity at typical field water contents
ET	Evapotranspiration
FC	Field capacity
MC	Moisture content
SIP	Soil Imaging Penetrometer^{TM}
SIS	Soil Information System^{TM}
SP	Saturation percentage
STI	Soil & Topography Information, LLC
TCYL	Total crop yield loss
TAW	Total available water
WP	Wilting point

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CHAPTER I

INTRODUCTION: IMPORTANCE OF SOIL INFORMATION IN PRECISION AGRICULTURE AND INTERNSHIP SUMMARY

The need for precision agricultural applications has been increasing in recent years, as farm managers continuously seek new methods and strategies to increase their returns on investment under increasingly stringent economic constraints and environmental regulations. In order to utilize the full potential of precision agricultural applications, a major challenge is the optimum application of irrigation water and maintaining the optimum water content in the soil based on crop needs given the spatial and temporal uncertainties due to the natural variability of soils and climatological conditions. Design of precision irrigation and drainage systems that can increase crop yield while minimizing water consumption and adverse impacts of agricultural discharge waters on the environment in the face of these uncertainties is an important task, and opportunity, for civil engineers.

Precision irrigation systems, such as drip irrigation and variable speed center pivot systems, can help farm owners and managers to increase their return on investment by reducing water consumption and, often times, increasing the crop yield. Similarly, precision drainage systems can help reduce excess water stress, which can lower crop

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yield, by maintaining water table levels at the desired levels in humid areas where water table is typically high (e.g. Midwest). In arid regions (e.g. Western U.S.), drainage systems can also increase crop yield by providing a means to lower soil salinity, which can reduce soil's productivity, by preventing accumulation of salts in soil due to irrigation.

While potential benefits of precision irrigation and drainage systems are well known, their widespread application is hindered due to the spatial variability of soil properties. Even in the same field, soil types and properties can vary significantly, which makes the design of precision agricultural systems a challenge. Quantifying the spatial variability in soil types and properties by collecting soil samples and analyzing them under laboratory conditions for field characterization is often time consuming and costly. One way of overcoming the high costs of traditional methods is to measure soil agricultural and hydraulic properties indirectly using in-situ tests, supplemented by geophysical data, that can be collected easily at low cost.

Addressing Spatial Variability of Agricultural and Soil Hydraulic Properties Using Easily Obtained Soil Physical Properties

Indirect measurement of soil agricultural and hydraulic properties using practical in-situ test equipment, such as cone penetrometers, has been subject to extensive research in soil sciences and water resources engineering (Vaz and Hopmans, 2001; Rooney and Lowery, 2000; Grunwald et al., 2001). Among others, cone penetrometers have proved particularly useful and become widespread for agricultural data collection and analysis, partially due to the well established cone penetrometer test literature first developed in the field of geotechnical engineering to measure soil engineering properties (Schmertmann, 1978, Robertson and Campanella, 1983a, Robertson and Campanella, 1983b, Coduto, 2001). The research on cone penetrometers has shown that tip resistance and sleeve friction values have unique correlations with different soil textures, which can be used for soil classification. Sensors attached to the penetrometers can provide real time, continuous data along various soil profiles during the test on other important soil features such as pore pressure and water content, which then can be used to interpret tip resistance and sleeve friction readings.

While cone penetrometers provide accurate information that can be used to infer on soil agricultural and hydraulic properties at each testing point, quantifying the spatial variability of soil properties at the field scale requires accurate interpolations between testing points. Geophysical data can complement the available soil information obtained at each testing point by improving knowledge of its spatial distribution, when appropriate statistical methods are used. Geophysical data used for this purpose include electrical resistivity (Kelly, 1977; Ahmed et al., 1988; Corwin and Lesch, 2003), seismic velocity (Rubin et al., 1992; Copty et al., 1993; Copty and Rubin, 1995; Hyridman et al., 1994), and ground penetrating radar (GPR) velocity (Hubbard et al., 1997, 1999). The accurate soil information obtained by processing penetrometer and geophysical data using advanced micro-correlations and other methods then can be used by growers to make managerial decisions.

Internship Site

The internship company, Soil & Topography Information, LLC (STI), is a consulting firm specializing in soil information systems. The internship site is STI's headquarters at 2453 Atwood Ave., Madison, Wisconsin 53704. STI currently has 20 employees specializing in information technologies and their applications in various fields such as geographic information systems (GIS), precision agriculture and site characterization.

STI (www.soiltopo.com) develops, evaluates, and deploys advanced systems for the creation of high-intensity, 3-D, soil and topography information. STI produces high-resolution topography maps and related information such as aspect, slope, and other landscape position attributes and 3-D Digital Soil Maps with accurate information about soil compaction, texture, moisture, resistivity, color, plant available water, wilting point and field capacity using cone penetrometer field tests and geophysical data.

The Soil Information System (SIS) developed by STI combines information at a rate, resolution, and format that makes it feasible to map soil at a scale useful for crop and hydrological models, nutrient and water budgeting, and other precision monitoring and management applications. STI's SIS technology "develops and deploys tools and techniques for digital, 3-D mapping of soil and topography at the field and landscape scale. STI's patented technology optimizes the process of soil and topographic surveying through the use of real-time sensors, positioning technologies, and mobile Internet applications. Resulting maps are integrated with airborne or spaceborne imagery, weather and climate data, management and land use information and exported as information maps for model and decision support applications" (Soil & Topography Information 2005).

The innovative Soil Imaging Penetrometer (SIP) developed by STI constitutes part of the core of the Soil Information System (SIS) of STI. The SIP provides geophysical data by analyzing soil images using image processing principles. With the analysis of soil images obtained by Soil Imaging Penetrometer, soil information can be obtained over large areas fast for a much lower cost.

CHAPTER II

PROBLEM DESCRIPTION

While STI's soil maps have been used for a wide variety of purposes, the company believed that there were other potential applications for use in engineering. One potential application was to develop precision irrigation and drainage systems using STI's soil maps. While soil maps provide various information about soil agricultural properties, this information was yet to be integrated with irrigation and drainage systems design.

Thomson and Threadgill (1987) report that center pivot irrigation systems account for about half of all sprinkler irrigated land area in the United States today and as of 1983 4.1 million hectares were irrigated under center pivots. The low labor and maintenance requirements, convenience, flexibility, performance and easy operations have made the center pivot the system of choice for agricultural irrigation in many parts of the US (New and Fipps, 2005). Center pivot systems have continuously improved for better performance since their introduction in 1950s (New and Fipps, 2005). Soil and Topography Information believed that further improvements in the performance of center pivot systems required an integrated, systems approach that takes into account agricultural soil and crop properties, both spatially and temporally.

A major objective of this internship was to investigate the potential and ways to integrate soil information with center pivot irrigation systems to improve their operation. In order to achieve this integration, an optimum center pivot operation strategy was investigated for spatial and temporal variability in soil conditions and the effect of this variability on crop yield.

Soil and Topography Information also believed that another use area for its precision soil maps was drainage systems design and construction. Similar to the deficit water stress, drainage of agricultural fields plays an important role in precision agriculture, as excess water stress due to accumulated water in the soil can significantly reduce crop yield. Therefore, in order to maintain the optimum water content in the soil to maximize crop yield, farm owners and managers should remove the excess water from the soil. While in relatively pervious soils, the excess water can drain without creating excess water stresses for the crops due to the high hydraulic conductivity, in many soils drainage systems are essential to remove the excess water from the soil for better crop yield, particularly when the water table is high. For example, it is reported that in the Midwest, which is home to some of the most productive agricultural lands in the nation, more than 50 million acres of land is artificially drained, both through surface and subsurface drainage systems for sustainable agricultural productivity (Agricultural Drainage Management Systems Task Force website, 2006).

While drainage systems have been extensively utilized in many parts of the country for improved crop yield, recent studies have shown that subsurface drainage systems can also contribute to excessive nitrogen release from agricultural fields into surface water bodies, when subsurface drainage systems are over designed (Skaggs, personal communication). This problem is exacerbated as drainage contractors mainly rely on experience as their primary design aid and use the same drain depth and spacing in their installations for different soil series (Atherton et al., 2004; Skaggs, personal communication, January 6, 2006). Optimal drainage system design using precision soil data would reduce unnecessary capital investment costs to construct drainage systems for farm owners, while reducing the excessive nitrogen releases into surface water bodies by eliminating over design.

The second major objective of this internship was to investigate the potential and ways to integrate soil information with drainage systems design and construction. Although drainage system design guidelines and methods are well established, they typically assume homogeneous soil conditions (NRCS, 1973). Field scale variation in soil properties can impact the effectiveness of subsurface drainage systems. For example, presence of profile layers of low conductivity can greatly retard drainage by affecting the flow pattern in the soil (Hillel, 1998), which may result in suboptimal drainage design. Atherton et al. (2004) reported that soil hydraulic behavior can be different even at within the same soil series and the large number of samples needed to properly estimate the hydraulic conductivity of the soil due to inherent spatial variability in the soil is a major challenge for designing better drainage systems. Drainage design could be improved by incorporating high resolution soil information using STI's Soil Information System.

While excess and deficit water stresses can be addressed by irrigation and drainage systems, another major problem that can reduce crop productivity is soil salinity. Salinity is the salt accumulation in soil due to salt contained in the irrigation water that is left behind in soil when the pure water passes back to the atmosphere through the process of evapotranspiration (Corwin and Lesch, 2003). Corwin and Lesch (2003) report that it is estimated that half of the worldwide irrigation systems (totaling about 250 million ha) are affected by salinity and waterlogging and salinity remains to be a major problem in the USA that limits agricultural productivity. Although the adverse effects of salinity on crop productivity are well known, practical techniques to diagnose and measure soil salinity have emerged only recently. As technological developments continue and improved, more practical geophysical measurement tools and technologies are introduced, research on improved, more practical methods to diagnose and measure soil salinity using these tools and technologies remains to be an active area of research.

The third major objective of this internship was to investigate the potential use of STI’s electrical resistivity measurements obtained with the resistivity sensors located on its soil probes in assessing soil salinity. The research (Rhoades et al., 1989; Corwin and Lesch, 2003; Lesch and Corwin, 2003) has shown that soil salinity can be assessed indirectly by measuring the electrical conductivity of dissolved salts in the soil solution. As electrical conductivity is the reciprocal of electrical resistivity, soil salinity can be quantified through resistivity measurements in terms of the total concentration of the soluble salts as measured by the electrical conductivity of the solution in deciSiemens per meter (dS/m) (Corwin and Lesch, 2003). Based on this theoretical relationship, it was hypothesized that soil salinity can be diagnosed and measured using the electrical resistivity measurements obtained by the resistivity sensors on STI’s soil probes. As part of this internship, the validity of STI’s field resistivity measurements as a means to diagnose and measure soil salinity was investigated using the relationships and theory reported in the literature.

CHAPTER III

DEVELOPMENT OF VARIABLE SPEED CENTER PIVOT IRRIGATION SYSTEM OPERATION PRESCRIPTION

Introduction

The first problem that was investigated under this internship involved development of a variable speed prescription for a center pivot irrigation system in operation on a farm in Nebraska. STI investigated and developed, under contract with John Deere various precision agricultural applications for an agricultural field that has been irrigated by a center pivot system. The field had a number of management zones, each with different crop and/or soil types. STI has collected and processed the data using the SIS and detailed 3-D soil maps have been created for the field. Based on these maps, a major task of the project involved optimizing the center pivot operation for optimum crop yield production throughout the field.

The need for the optimization of the pivot system operation arose from the unusual constraints and the terrain conditions imposed on the center pivot irrigation system. Unlike circular fields irrigated with center pivot systems typically at a constant speed, about one fourth of the field was excluded from farming due to unsuitable topography, leaving only three quarters for irrigation by the center pivot. This constrain required the center pivot to operate like a “windshield wiper” and stop every time the field boundary is reached and start irrigating the field in the reverse direction until the other end of the field is reached again. The “windshield wiper” operation could potentially cause uneven irrigation water application. For example, if the center pivot is operated at a constant speed, the end zones would be irrigated twice with a short time interval in between, first before the pivot comes to stop, and for the second time when the pivot changes its direction and starts its next trip. The end zones then wait for the next water application until the pivot completes its trip to the other end zone and comes back. On the other hand, the zones in the middle of the field are irrigated in the middle of each sweep of the pivot with constant time intervals between each irrigation. This may cause excessive irrigation amounts at the end zones within a short duration of time and then a long waiting period until the pivot comes back again, during which water content of the soil may drop below the critical limit causing crop yield losses. Given the variable soil and crop properties, such as soil water holding capacities and crop resistance to deficit water stress, what should be the optimum center pivot operation prescription that would maximize the overall crop yield?

A Dynamic Programming Approach to Develop Variable Speed Center Pivot Operation Prescription

One way of optimizing the center pivot irrigation was to dynamically adjust flow rates from each nozzle located along the center pivot based on the spatial and temporal irrigation needs. Another way was to develop a variable speed prescription for the center pivot operations. Ultimately both solutions can be integrated for a more robust operation scheme. In this project, center pivot manufacturing company undertook the task of optimizing the variable flow rates, while STI undertook development of a variable speed prescription assuming a constant (i.e. maximum) flow rate. The center pivot irrigation hardware layout is shown in Figure 1.

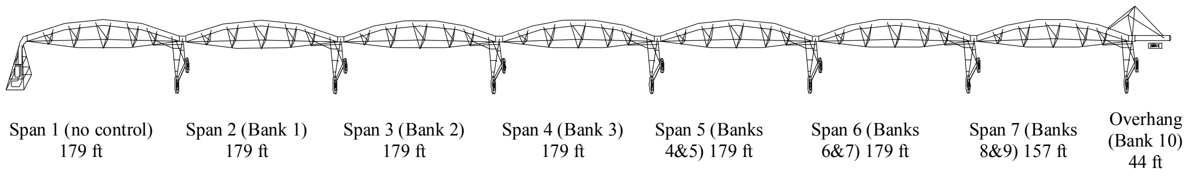


Fig. 1. Center pivot hardware layout

In order to address the above described problem, a dynamic programming approach was adapted for development of a variable speed prescription that takes into account water balance spatially across the field based on different soil and crop properties. Dynamic programming is an effective methodology that is used to decompose a multiple variable problem into a sequence of related problems each having one decision variable (Deuermeyer and Curry, 1989). This approach is particularly appropriate for multiple period decision problems, where an optimal decision should be made during each period. The reader is referred to Nemhauser (1967) for more details on dynamic programming theory and its applications to various problems.

Cost Function

The cost function to be minimized to determine the optimal center pivot operation strategy was composed of two components. The first component was the crop yield loss, which is a function of the soil moisture content and the crop's water consumption characteristics. The second component was simply the cost of the irrigation water applied. The objective function to be optimized to determine the optimal center pivot operation strategy (i.e. sequence of times allotted for irrigation of each bank-segment) is shown in Equation 1.

$$\min \sum Cost = \sum_{i=1}^{n} f_{yieldloss}(t_i) + \sum_{i=1}^{n} f_{water\cos t}(t_i) \qquad (1)$$

The left hand side of Equation 1 is the total cost that incurs as a result of the selected center pivot operation strategy at the end of the simulation. The first component in the right hand side represents the losses that incur due to crop yield losses as a result of soil moisture content falling below the critical depletion. Critical depletion is the soil moisture content, below which the crop yield loss starts as a result of the water deficit stress. The yield loss component of the cost function depends on the irrigation duration, t_i, because higher the irrigation duration (and flow rate), lower the likelihood that the crop yield loss will occur as the stored irrigation water would prevent the soil moisture content to fall below the critical depletion which triggers the crop yield loss. In the case that no water is added to the soil, this crop yield loss continues as the soil water is lost to the atmosphere reducing the plant available water as a result of the transpiration process at a decreasing rate until the wilting point. At the wilting point, the crop is lost permanently corresponding to the crop yield loss of 100%. The second component in the right hand side of Equation 1 represents the cost of the irrigation water, which is also a function of the irrigation duration, t_i.

The objective of the optimization process was to avoid any yield loss by maintaining the soil moisture content above the critical depletion at all times at any bank-segment, while minimizing the free drainage of the excess irrigation water, which can be used on another bank segment to keep the crop away from the critical depletion. This objective essentially requires keeping the soil moisture content at all bank-segments between the critical depletion and the field capacity, which is defined as the amount of soil water content held in the soil pores after excess irrigation water drains away, typically within two to three days after the irrigation. Plant soil water characteristics and their impact on the evapotranspiration process are shown in Figure 2.

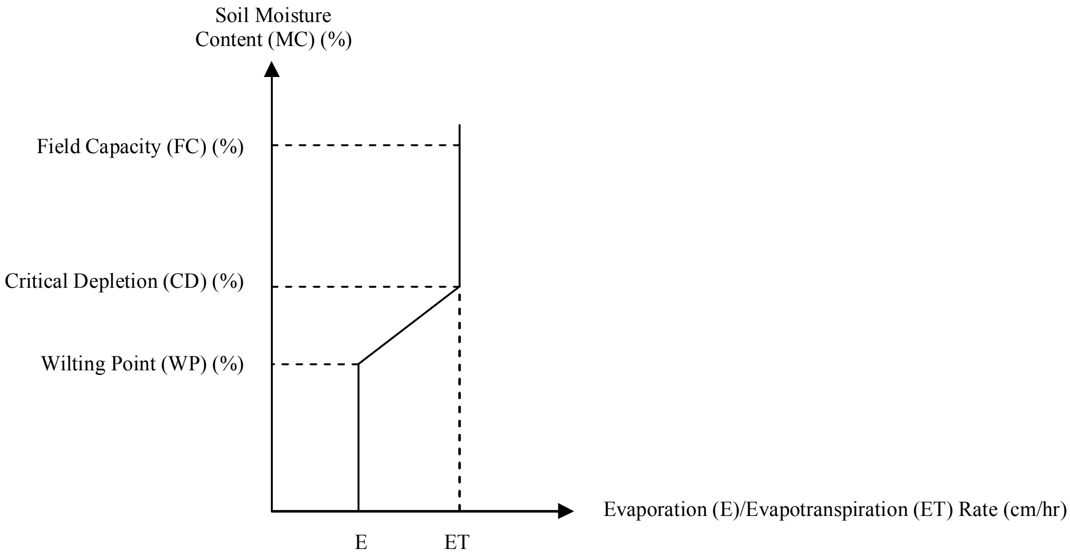


Fig. 2. Critical soil water contents for crop growth and their impact on evapotranspiration process

In Figure 2, the critical depletion (CD) represents the soil water content, below which the crop yield loss starts to occur because the soil no longer has sufficient water to meet all the water consumption needs of the crop. This crop yield loss continues to increase as the soil water content continues to decrease until the wilting point (WP). Below the wilting point, the crop roots can no longer extract water from the soil and the crop wilting takes place.

Spatial Variability of Soil Properties

As one of the main objectives of the SIS is to optimize the irrigation water application as a function of spatial soil variability, the first step of the optimization formulation was to identify this variability in the field. The important soil properties that would be needed in the optimization formulation, such as field capacity, critical depletion and wilting point, were estimated by the SIS. This characterization yielded 13 management zones, which were approximated based on their varying soil properties as shown in Figure 3 and Figure 4 and summarized in Table 1.

Table 1. Management zones based on soil, terrain and crop properties

Zone #	Description	Zone #	Description
1	Corn	8	Corn
2	Corn (top swale)	9	Corn*
3	Corn (bottom swale)	10	Corn (bottom swale)*
4	Corn (bottom swale)	11	No crop*
5	Corn (top swale)	12	No crop*
6	Corn (bottom swale)	13	No crop*
7	Soybeans		

* Outside of irrigation arm

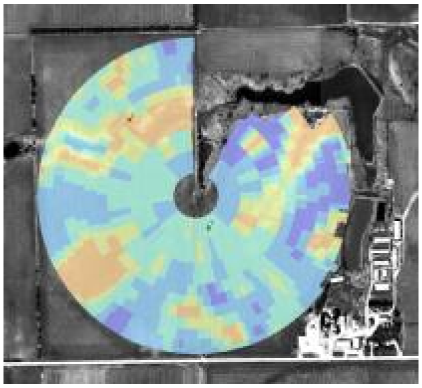


Fig. 3. Soil water holding capacity distribution obtained by SIS and summarized by banks

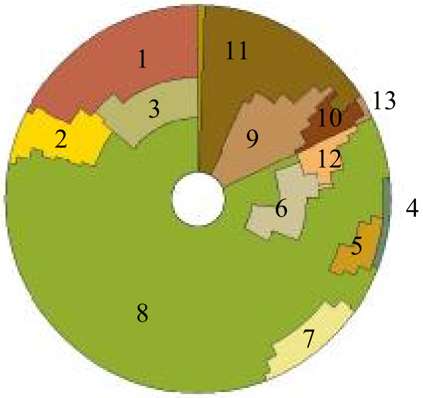


Fig. 4. Soil management zones approximated for soil water holding capacity distribution

In order to create decision points across the field during the simulation, the field was divided into 10 slices as shown in Figure 5. By dividing the field into slices, the problem was decomposed into a collection of interrelated subproblems with the decision variable for each subproblem being the duration the pivot spends on each slice. The set of durations for all slices (i.e. subproblems) that yields the maximum crop yield for the entire field was then sought as the optimal set of durations. The sum of all slices (i.e. 297 degrees) represents the total area of the field irrigated by the pivot. Because the end slices serve as a boundary condition for the simulation, where the pivot comes to a stop and reverses its direction, these slices were assigned a small area (i.e. a short bank-segment distance) in order to approximate an instantaneous reversal in the direction of the pivot. The size of the each remaining slice was determined by dividing the total field by the number of slices (i.e. 8). The number of slices was determined in a way to limit the computational effort, while allowing enough variability in the moisture content among the slices during the simulation.

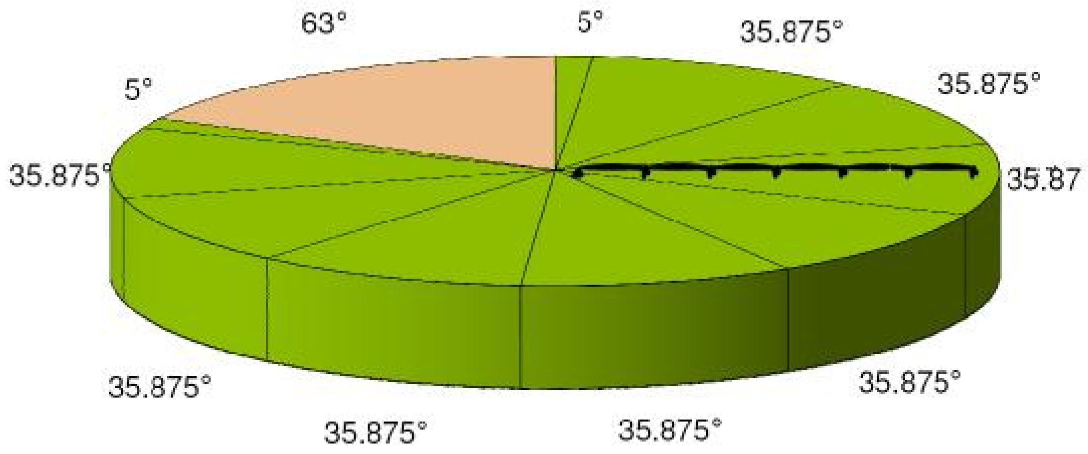


Fig. 5. Decomposition of the field for the determination of optimum pivot speeds prescription

Data

Other data used to estimate the objective function in the simulations came from various sources. These sources are briefly described below:

Evapotranspiration Rate

Evapotranspiration rate was obtained from Accuweather measurement station located in Lincoln, Nebraska. The evapotranspiration rate (ET_o) measured by Accuweather for the reference plant (i.e. grass) was adjusted by the evapotranspiration adjustment coefficient for corn, which is 1.1, by multiplying the standard ET_o with this coefficient. Because the ET rate changes over time with weather conditions, the average ET_o measurement that corresponds to the period between 7/1/2005 and 7/14/2005 was selected for use in the simulations.

Root Zone Depth

The average root zone depth across the field was used for all bank-segments in all simulations, which is 121 cm and assumed to be uniform across the field. The root zone depth was measured by SIS as the depth which corresponds to a limiting tip and sleeve friction resistance value that the plant roots cannot overcome for penetration during growth. The root zone depth was used to calculate the volumetric water content of the soil at all steps of the simulations.

Maximum Yield

The maximum yield was assumed to be the anticipated yield under normal conditions with no water deficit stress. This data was obtained from experts through personal communication. Accordingly, anticipated yield for commercial corn under a center pivots was assumed between 175 bushels and 225 bushels. The yield for specialty corns tends to run between 160 bushels and 180 bushels per acre.

Cost of Yield Loss

Value of corn yield and subsequently the cost of yield loss was estimated again using current market prices obtained from experts through personal communication. The value of #2 yellow corn was approximately between $1.75 per bushel at harvest and $2.70 per bushel if it was contracted earlier in the year. This type of corn is typically plain commercial corn like what is sold into ethanol plants, exports, large feed lot's, etc. The value of a specialty corn, such as white corn, high starch corn, corn with a defined value such as food grade for a corn chip manufacture would have additional value of $0.20 to $0.50 above the commercial corn. In this study, #2 yellow corn was assumed to be the dominant crop type across the field and the unit price of $1.75 per bushel was assumed to be the value of the crop. This unit price was then used to estimate the cost of the yield loss in the simulations using Equation 2.

Irrigation Flow Rate

Although the optimum speed prescription was going to be obtained for the maximum bank flow rates initially, for some banks it was observed that the maximum flow rate would be significantly higher than the ET measurements. In the initial estimations, this resulted in too high soil moisture contents in the field at all times significantly reducing any yield loss cost to occur in the simulations. Because the objective was to find an optimum or, at least, an improved speed prescription in comparison with the current one, the flow rates were reduced to ET rate where necessary in order to make the soil water balance equation more sensitive to changes in the soil moisture content.

Cost of Water

The cost data for irrigation water was obtained from an expert in this area (Mark Stelford, personal communication). The cost of a gallon of water can be determined in many ways. However, at the time of the simulation, the approximate cost of water in Midwest was about $95.78 per acre for 20 acre inches pumped. In the simulations this unit cost was used.

Hydrologic Balance Equation

In addition to the dynamic programming formulation, hydrologic balance principle should also be utilized in the optimization of the center pivot operations in order to forecast the soil moisture contents and ET_{adj} over time, which, in turn, can be used to estimate the yield loss using Equation 2. The hydrological balance of the soil was modeled based on the principle of conservation of mass, which states that any change in the moisture content of the soil is the difference between incoming and outgoing flows for a given soil volume (Linsey and Franzini, 1987). The hydrological systems to be modeled with the water balance equation typically involve various variables such as initial soil moisture, effective precipitation, evaporation, evapotranspiration, and crop water requirements and can be summarized as shown in Figure 6 and Equation 3.

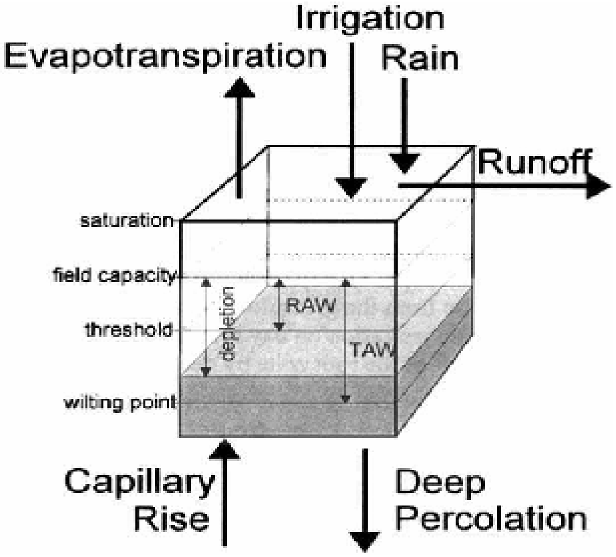


Fig. 6. Illustration of the water balance equation (FAO, 1998)

In Figure 6, the total available water (TAW) is the difference between the field capacity and the wilting point and represents the water available for crops, although the reduction in soil water content below the field capacity increasingly causes crop yield loss until the wilting point, at which the entire crop is lost due to lack of water.

$$\textit{Precipitation} + \textit{Irrigation} + \textit{Capillary Rise} - \textit{Evapotranspiration} - \textit{Runoff} - \textit{Storage} - \textit{Deep Percolation} = 0 \qquad (3)$$

In this study, only irrigation, evapotranspiration and storage components were considered, while precipitation, runoff, capillary rise and deep percolation components were ignored because the current study was exploratory, the focus of the study was the operation of the center pivot only and other components would be included in a more comprehensive model at a future date. A more The soil water content of each management zone was calculated using the hydrologic balance principle at every time step as the center pivot travels across the field back and forth. The impact of deficit water stress, if any, on crop yield was evaluated spatially at every time step. Any crop yield loss in the slices due to deficit water stress penalized the objective function and forced the formulation to seek a better set of sequential durations for all the slices, until the maximum crop yield with the lowest total cost was reached as the optimality criterion. The components of the simplified water balance equation used in this study are shown in Figure 7 below.

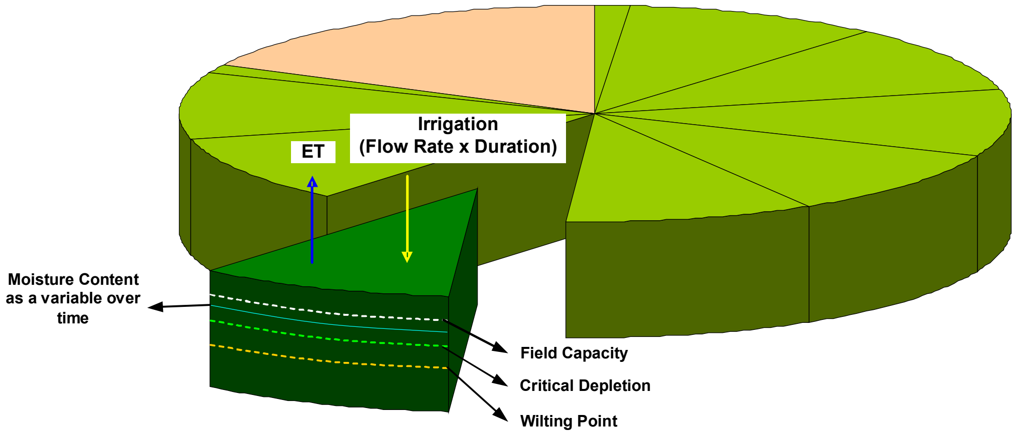


Fig. 7. Illustration of the soil water characteristics and water balance principle used in the simulation model

Figure 7 illustrates the field wide critical soil water contents illustrated in Figure 2 earlier combined with the evapotranspiration and irrigation components of the soil water balance equation in three dimensions. The illustration is given for only one slice for simplicity. The blue continuous line in the selected slice represents the moisture content varying between the field capacity, critical depletion and wilting point as a function of evapotranspiration (ET) and irrigation, which is the product of the flow rate of the pivot nozzles and the duration of irrigation. While the soil water characteristics can vary for each slice as a function of soil properties, the flow rate is the decision variable of the simulation and can vary for each slice.

Current Center Pivot Operation Strategy

The center pivot's current speed program before the optimization was a variable speed program that involved varying irrigation water application rates as shown in Table 2, Table 3 and Figure 8. This prescription applied irrigation water at the beginning of each sweep at lower speeds (i.e. 50% and 80%) until the mid field is reached. The pivot speed was then increased to maximum until the end of the field is reached. The prescription was then reversed during the trip back to the initial position.

Table 2. Pivots speed prescription before optimization

Section	Clockwise (% max. application rate)	Counter Clockwise (% max. application rate)
A	50%	100%
B	80%	200%
C	100%	80%
D	100%	50%

Table 3. Approximated relative pivot speed prescription speeds before optimization

Section	Clockwise (speed ratios)	Counter Clockwise (speed ratios)
A	2.57	0.86
B	1.00	0.80
C	0.80	1.00
D	0.86	2.57

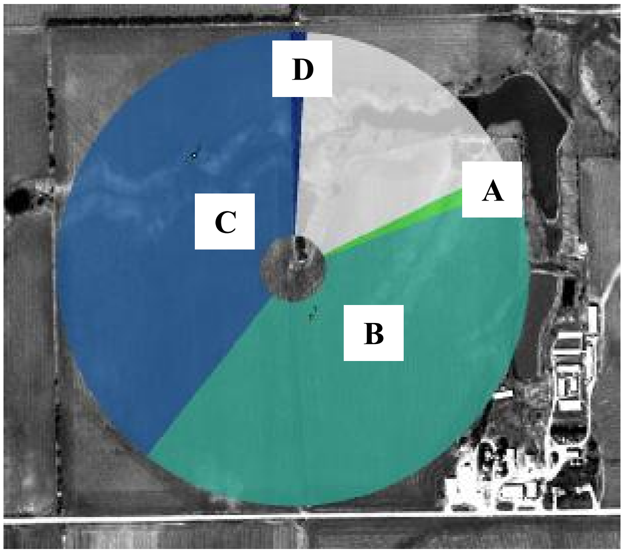


Fig. 8. Pivot's speed program before optimization

Although the above prescription had been applied at the field without any problems, it created difficulties during the simulation because of the requirement that maximum bank flow rates should be used at all times during the simulations and the variable flow rates were optimized by the manufacturer company. This requirement resulted in excessive irrigation water applications over slices A and D when the maximum flow rate was used. In order to overcome this restriction, while simulating the current speed program, the pivot speed was increased over the slices A and D such that the applied water and the resulting moisture content of the soil of these slices did not exceed the field capacity significantly. The speed program was then approximated in such a way that the total amount of water applied during each cycle (maximum flow rate x simulation cycle duration) would remain the same, while the approximated current prescription would represent the prescription in Table 2 as close as possible. The goal of the optimization was then to calculate the water and yield loss costs incurred by this approximated speed prescription and then to search for a prescription that would minimize this total cost.

Assumptions

The following assumptions were made in the simulations:

- Although soil water characteristics, such as field capacity and critical depletion, were obtained from point measurements employing the SIS, these values were assumed to be continuous across the management zones.
- Pivot velocities calculated from the irrigation durations for each bank-segment represent the pivot velocity along the centerline of the corresponding bank-segment.
- All crop management zones were assumed to have corn as the crop type.

- Evaporation rate (E), which also defined the wilting point, was assumed to be 0.00008 $cm^3/cm^3/hr$, as no evaporation measurements were available. This value was selected arbitrarily because the wilting point was never reached during the simulations. The soil water content remained around or above the critical depletion at all times during the simulations and, therefore, did not have any impact on the results.
- A linear reduction in evapotranspiration (ET) is assumed below critical depletion up to the wilting point as shown in Figure 2.
- Initial Condition (IC) was assumed to be Field Capacity - 0.03 in cm^3/cm^3 in order to maintain the soil water content around the critical depletion throughout the simulation period and to increase the sensitivity of the cost function (i.e. crop yield loss) to the speed prescription.
- Precipitation was ignored.
- Total crop yield loss (TCYL), if any, was assumed as the average of all crop yield losses (CYLs) calculated at each period (e.g. $TCYL = (CYL_i + CYL_{i+10} + CYL_{i+20} + CYL_{i+30} CYL_{i+40} + CYL_{i+50} + CYL_{i+60}) / 6$).
- All fixed costs of pivot operations were ignored.

Results

Because the objective of the optimization model was to determine whether there was an optimum speed prescription in comparison to the existing one, the optimization was conducted for one bank at a time with the assumption that if an optimum prescription can be obtained for one bank, it can be extended to other banks too. Therefore, the optimization-simulation model was run for only bank #2 and bank #8, which covered management zones 1, 5, 7 and 8. In addition to these two simulations, a symmetric speed prescription, which initially appeared as a candidate for the optimal strategy, was also tested. In all simulations, the simulation period was 340 hours, during which the pivot completed two cycles. The results of the simulations are summarized below.

Bank # 2, Management Zones 5 and 8

In the first simulation, the optimum speed prescription was sought for bank # 2, which has the management zones 5 and 8. The strip irrigated under bank #2 covered management zone 5 (slice #9) and management zone 8 (slices from 1 to 8 and slice 10), which had different soil water characteristics. The effect of the different soil water characteristics in these two management zones are illustrated by the dips in field capacity, critical depletion and wilting point lines in Figure 9b. The initial moisture content was assumed to be field capacity minus 0.03 cm^3/cm^3 for both management zones. The soil water characteristics obtained by the SIS and the other parameters assumed to conduct the simulations are shown in Table 4 and Table 5.

Table 4. Input data of the simulations for bank #2 for management zone #5

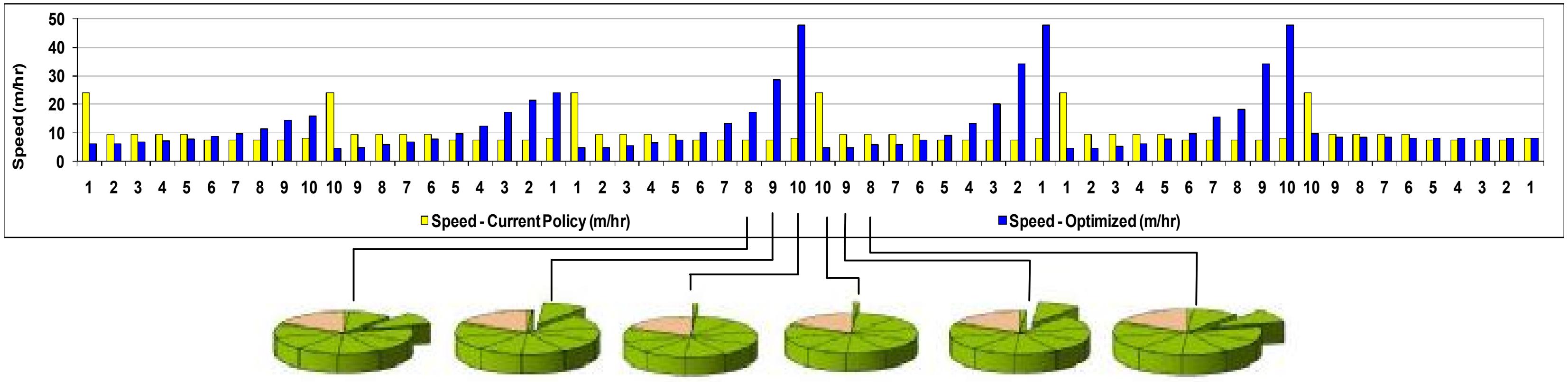
Parameter	Value	Source
Field capacity (cm^3/cm^3)	0.33800	SIS
Critical depletion (cm^3/cm^3)	0.28500	SIS
Wilting point (cm^3/cm^3)	0.15900	SIS
Initial moisture content (cm^3/cm^3)	0.30800	Assumed
Hygroscopic moisture content (MC_{min}) (cm^3/cm^3)	0.01000	Assumed
Evapotranspiration (ET) rate (cm/cm/hr)	0.00029	Assumed
Evaporation (E) rate (cm/cm/hr)	0.00008	Assumed
Soil thickness (cm)	121	SIS
Total degrees irrigated by pivot	297	Topography
Maximum flow rate of bank #2 (gals/min)	59.34	CP manufacturer co.
Cost of water ($/$cm^3$)	4.67×10^{-8}	Expert opinion
Price of corn ($/acre)	471.7	Expert opinion

Table 5. Data used in the simulations of bank #2 for management zone #8

Parameter	Value	Source
Field capacity (cm^3/cm^3)	0.34905	SIS
Critical depletion (cm^3/cm^3)	0.29630	SIS
Wilting point (cm^3/cm^3)	0.17000	SIS
Initial moisture content* (cm^3/cm^3)	0.34905	Assumed
Hygroscopic moisture content (MC_{min})* (cm^3/cm^3)	0.01000	Assumed
Evapotranspiration (ET) rate* (cm/cm/hr)	0.00029	Assumed
Evaporation (E) rate* (cm/cm/hr)	0.00008	Assumed
Soil thickness (cm)	121	SIS
Total degrees irrigated by pivot	297	Topography
Maximum flow rate of bank #2 (gals/min)	59.34	CP manufacturer co.
Cost of water ($/cm3)	4.67 x 10-8	Expert opinion
Price of corn ($/acre)	471.7	Expert opinion

The simulation of the current speed program showed that this prescription is likely to result in soil moisture content falling below the critical depletion, which triggers the yield loss penalty. Although the total number of simulation cycles (i.e. 3) in the simulations did not allow the long term effects of this prescription on the yield loss, it was nevertheless observed that the dips below the critical depletion tended to increase over time for certain slices (Figure 9b). As a result, an optimized speed prescription would have to eliminate the yield losses incurred as a result of these dips.

When the speed program was optimized, the optimum speed prescription was determined as the one that keeps the moisture content from falling below the critical depletion throughout the simulation for all slices as shown in Figure 9a and Figure 9b. Figure 9a also illustrates the sequence of the slices looked at during the optimization and the correspondence between the slice numbers and the simulation periods.



Slice 8 (Period 28) Slice 9 (Period 29) Slice 10 (Period 30) Slice 10 (Period 31) Slice 9 (Period 32) Slice 8 (Period 33)

Fig. 9a. Current vs. optimized pivot speeds for bank #2, management zones 5 and 8

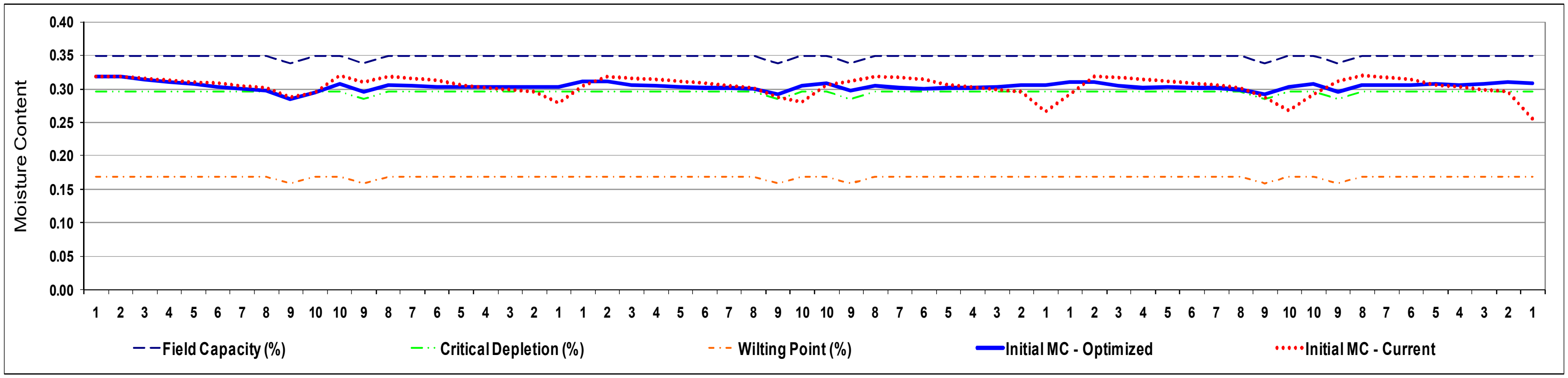


Fig. 9b. Comparison of $MC_{initial}$ values for the current and optimized policies for bank #2, management zones 5 and 8

When the cost components of the current and optimized speed prescriptions were analyzed, it is apparent that the water cost components are the same for both prescriptions as the total irrigation water amount applied throughout the simulation is the same for both prescriptions as flow rate was not a variable in the optimization model. As a result, Figure 9c shows that the total water costs converge to the same amount.

As expected, the major difference between two prescriptions was observed in the yield loss component as shown in Figure 9d. As illustrated in Figure 9b, the current prescription started incurring yield loss costs before the end of first cycle and continued increasing in a stepwise manner throughout the simulation. The yield loss cost was minimized to a great extend when the speed prescription was optimized in a way that eliminated the yield losses by maintaining the moisture content above the critical depletion for these slices (Figure 9a). Figure 9e shows the total costs of current and optimized prescriptions.

Bank # 8, Management Zones 1, 7 and 8

In a similar simulation, the optimum speed prescription was sought for bank # 8, which has the management zones 1, 7 and 8. The strip irrigated under bank #8 covered management zones 1 (slice #1 thorugh 3#), management zone 7 (slice #8) and management zone 8 (slices from 4 through 6 and 8 through 10), which had similar soil

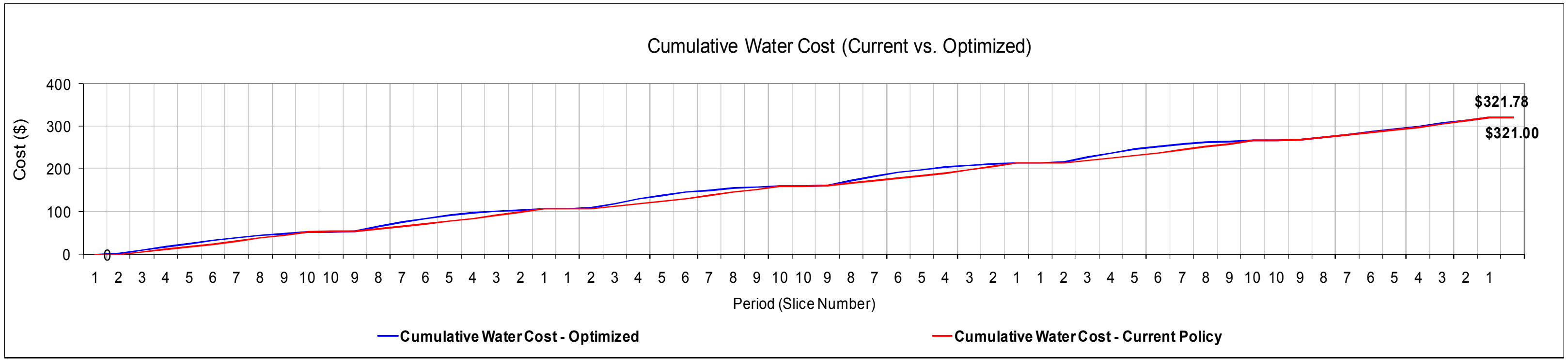


Fig. 9c. Comparison of cumulative water costs for the current and optimized policies for bank #2, management zones 5 and 8

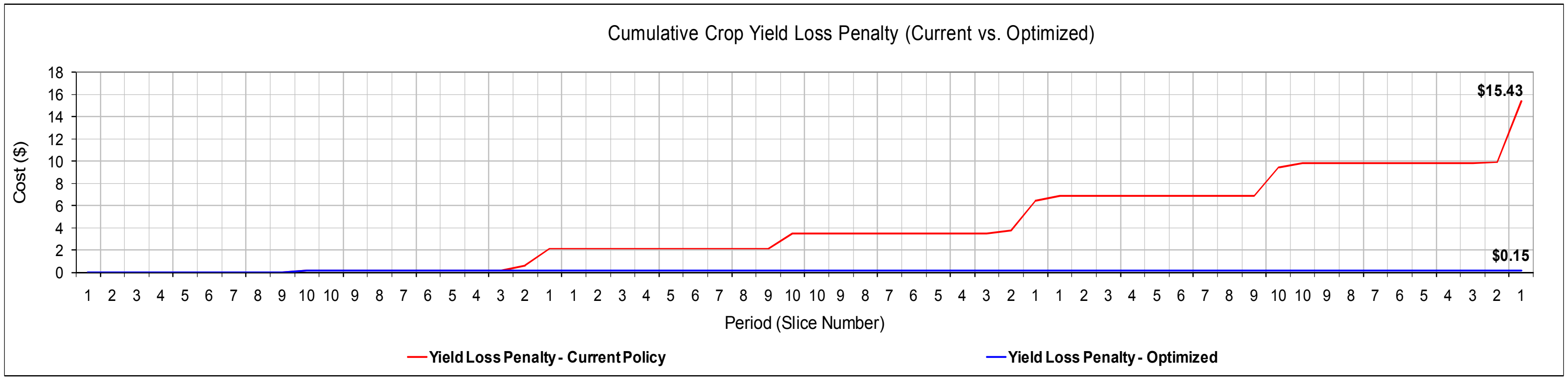


Fig. 9d. Comparison of crop yield losses for current vs. optimized pivot speed prescriptions for bank #2, management zones 5 and 8

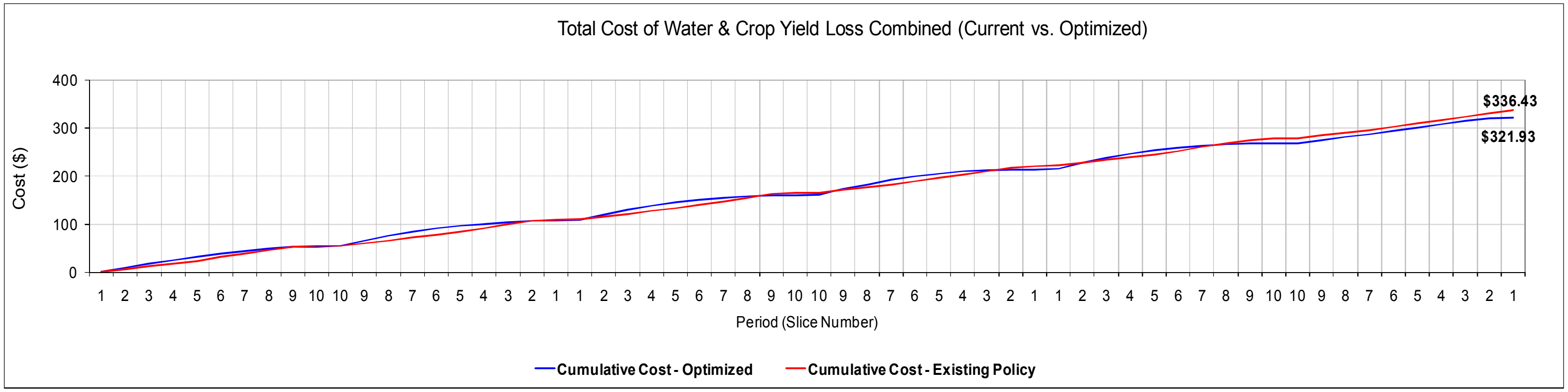


Fig. 9e. Comparison of total costs for current vs. optimized pivot speed prescriptions for bank #2, management zones 5 and 8

Table 6. Input data of the simulations for bank #8 for management zone #1

Parameter	Value	Source
Field capacity (cm^3/cm^3)	0.35000	SIS
Critical depletion (cm^3/cm^3)	0.29700	SIS
Wilting point (cm^3/cm^3)	0.17000	SIS
Initial moisture content (cm^3/cm^3)	0.32000	Assumed
Hygroscopic moisture content (MC_{min}) (cm^3/cm^3)	0.01000	Assumed
Evapotranspiration (ET) rate (cm/cm/hr)	0.00029	Assumed
Evaporation (E) rate (cm/cm/hr)	0.00008	Assumed
Soil thickness (cm)	121	SIS
Total degrees irrigated by pivot	297	Topography
Maximum flow rate of bank #2 (gals/min)	77.60	CP manufacturer co.
Cost of water ($\$/cm^3$)	4.67×10^{-8}	Expert opinion
Price of corn ($/acre)	471.7	Expert opinion

Table 7. Data used in the simulations of bank #8 for management zone #7

Parameter	Value	Source
Field capacity (cm^3/cm^3)	0.35000	SIS
Critical depletion (cm^3/cm^3)	0.29700	SIS
Wilting point (cm^3/cm^3)	0.17000	SIS
Initial moisture content (cm^3/cm^3)	0.32000	Assumed
Hygroscopic moisture content (MC_{min}) (cm^3/cm^3)	0.01000	Assumed
Evapotranspiration (ET) rate (cm/cm/hr)	0.00029	Assumed
Evaporation (E) rate (cm/cm/hr)	0.00008	Assumed
Soil thickness (cm)	121	SIS
Total degrees irrigated by pivot	297	Topography
Maximum flow rate of bank #2 (gals/min)	59.34	CP manufacturer co.
Cost of water ($/cm3)	4.67 x 10-8	Expert opinion
Price of corn ($/acre)	471.7	Expert opinion

water characteristics. The initial moisture content was assumed to be field capacity minus 0.03 cm^3/cm^3 for both management zones. The soil water characteristics obtained by the SIS and the other parameters assumed to conduct the simulations for management zones 1 and 7 are shown in Table 6 and Table 7.

As was the case in the previous simulation, the simulation of the current speed program for bank #8 showed that this prescription is likely to result in soil moisture content falling below the critical depletion, which triggers the yield loss penalty. Although the total number of simulation cycles (i.e. 3) in the simulations did not allow the long term effects of this prescription on the yield loss, it was nevertheless observed that the dips below the critical depletion tended to increase over time for certain slices (Figure 10b). As a result, an optimized speed prescription would have to eliminate the yield losses incurred as a result of these dips. When the speed program was optimized, the optimum speed prescription was again determined as the one that keeps the moisture content from falling below the critical depletion throughout the simulation for all slices as shown in Figure 10a and Figure 10b. It appears that three simulation cycles were sufficient to obtain steady state soil water content profiles because the soil water content

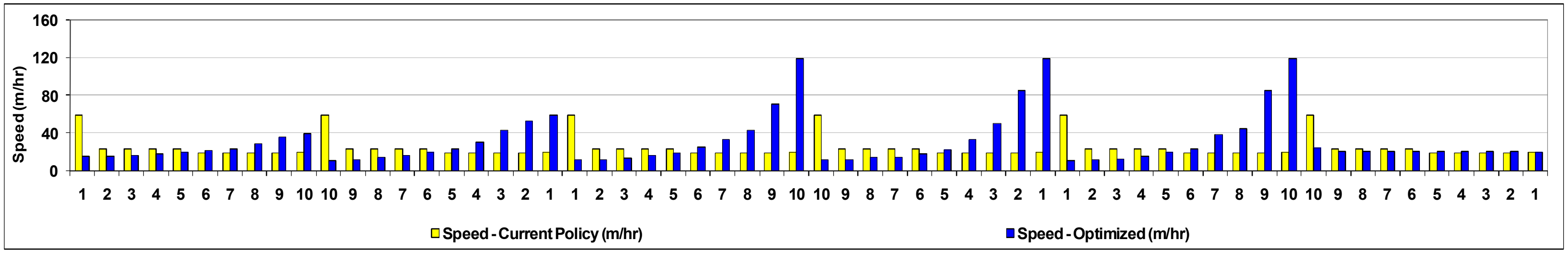


Fig. 10a. Current vs. optimized pivot speeds for bank #8, management zones 1, 7 and 8

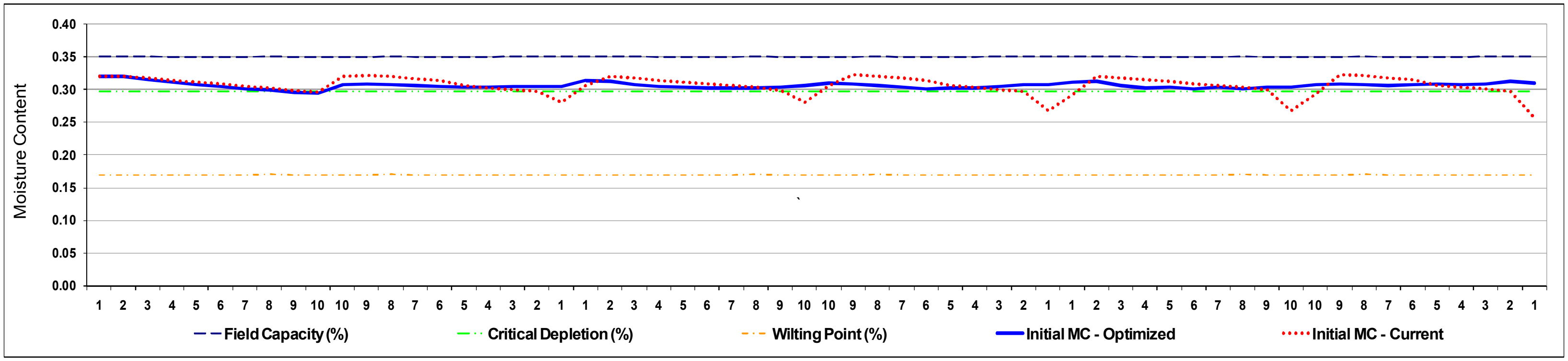


Fig. 10b. Comparison of $MC_{initial}$ values for the current and optimized policies for bank #8, management zones 1, 7 and 8

values appeared stable as early as the second cycle was reached. The transition period during the first cycle appears to be due to the uniform soil water profile assumed as the initial condition.

Similar to the simulation results of bank #2, the water cost components are the same for both prescriptions as the total irrigation water amount applied throughout the simulation is the same for both prescriptions (Figure 10c).

The major difference between two prescriptions was again observed in the yield loss component as shown in Figure 10d. As illustrated in Figure 10b, the current prescription started incurring yield loss costs before the end of first cycle and continued increasing in a stepwise manner every time the moisture content fell below the critical depletion throughout the simulation. The yield loss cost was minimized to a great extend when the speed prescription was changed to eliminate the yield losses by maintaining the moisture content above the critical depletion for all slices (Figure 10a). Figure 10e shows the total costs of current and optimized prescriptions.

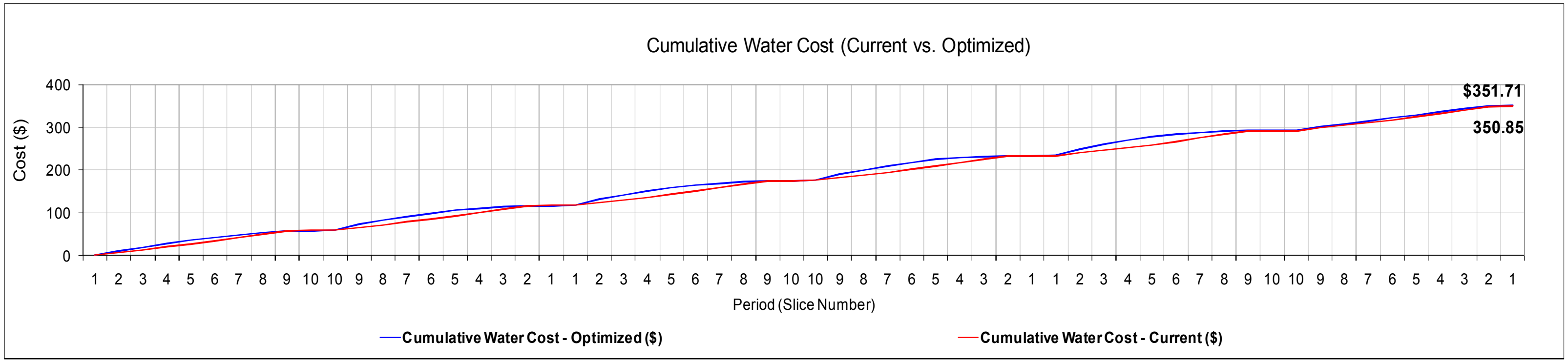


Fig. 10c. Comparison of cumulative water costs for the current and optimized policies for bank #8, management zones 1, 7 and 8

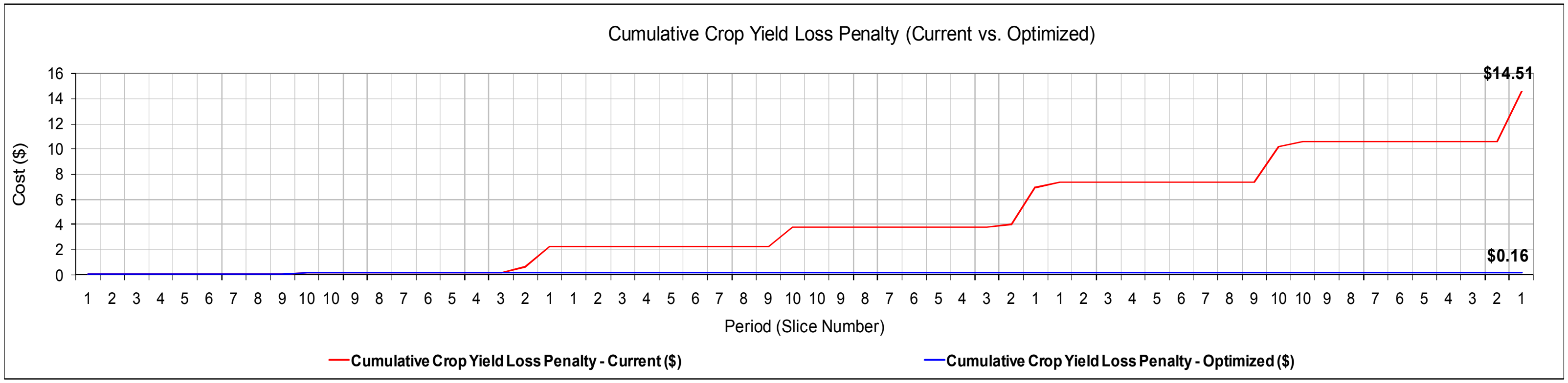


Fig. 10d. Comparison of crop yield losses for current vs. optimized pivot speed prescriptions for bank #8, management zones 1, 7 and 8

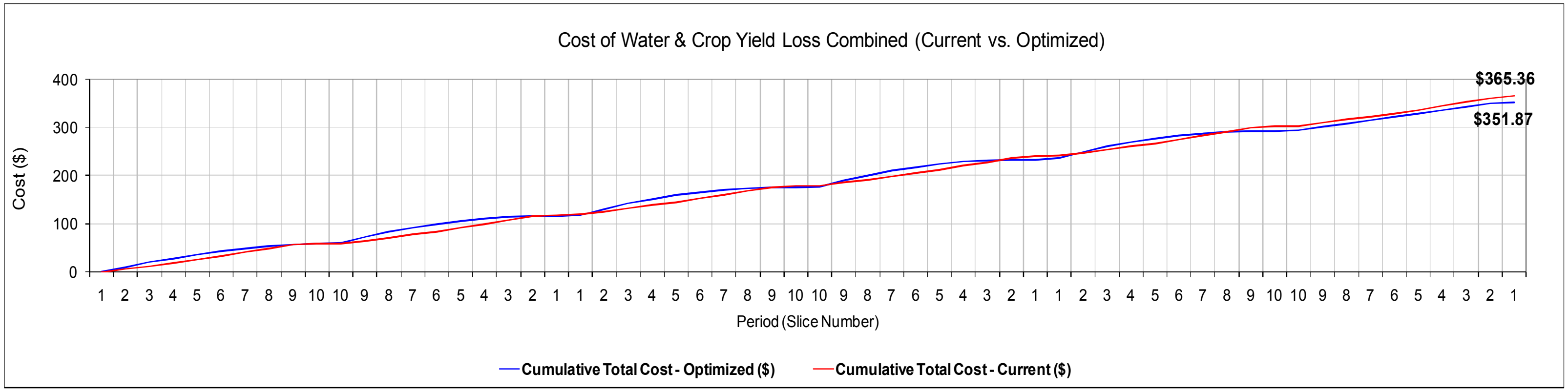


Fig. 10e. Comparison of total costs for current vs. optimized pivot speed prescriptions for bank #8, management zones 1, 7 and 8

Bank # 1, Management Zone 8

At the outset of the simulations, a candidate strategy for the optimum prescription was a symmetric prescription, in which the pivot started at a relatively faster speed and slowed down gradually as it approached the mid field and then accelerated towards the other end of the field (Figure 11a). As a last attempt, this symmetric speed prescription was tested in the simulations for bank #1, which had a single management zone (management zone #1).

Although it was expected to be an improved prescription compared to the current one, the simulation results showed that this prescription actually resulted in higher yield loss costs as it increased the dips and peaks in the moisture content values over time (Figure 11c). The optimization of the speed program eliminated these dips and peaks to a great extend and reduced the total cost of the symmetric speed distribution by $59.79 from $253.14 to $193.35. The impact of increasing soil water deficits below the critical depletion was particularly apparent towards the end of the simulation. The results of this simulation are shown from Figure 11b thorough Figure 11f.

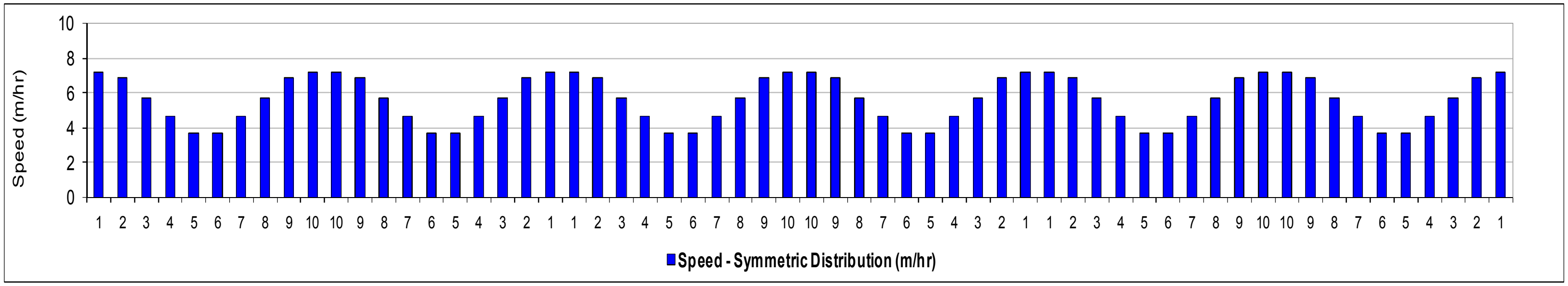


Fig. 11a. Symmetric pivot speed prescription for bank #1, management zone 8

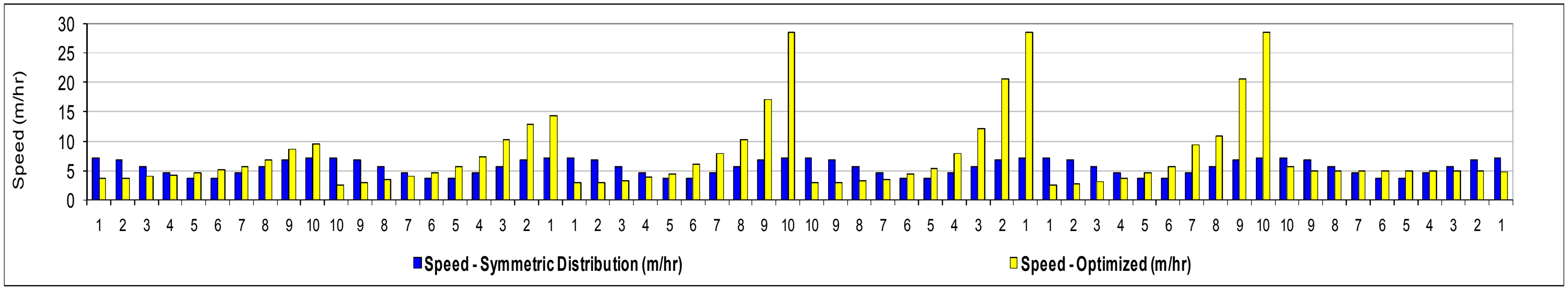


Fig. 11b. Symmetric vs. optimized pivot speed prescriptions for bank #1, management zone 8

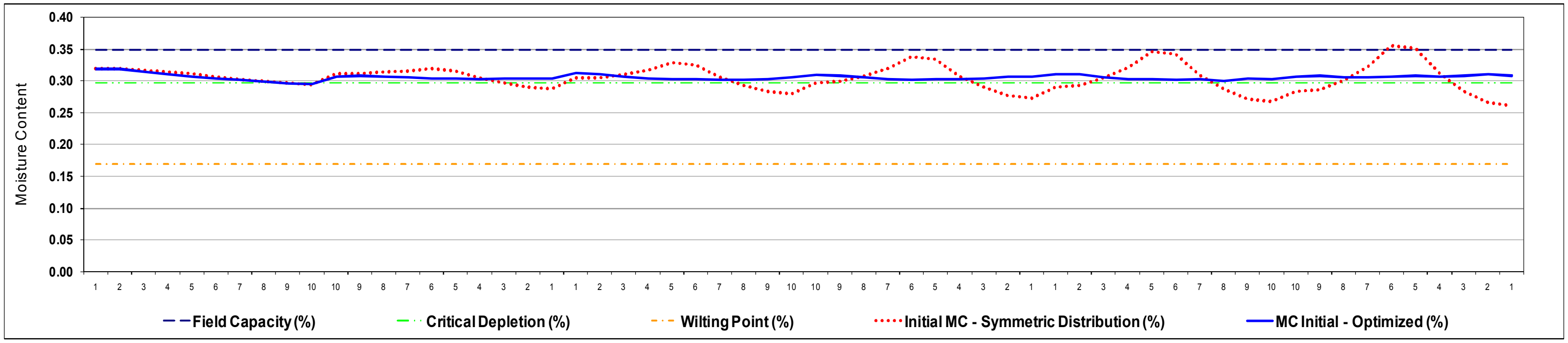


Fig. 11c. $MC_{initial}$ values for the symmetric pivot speed prescription for bank #1, management zone 8

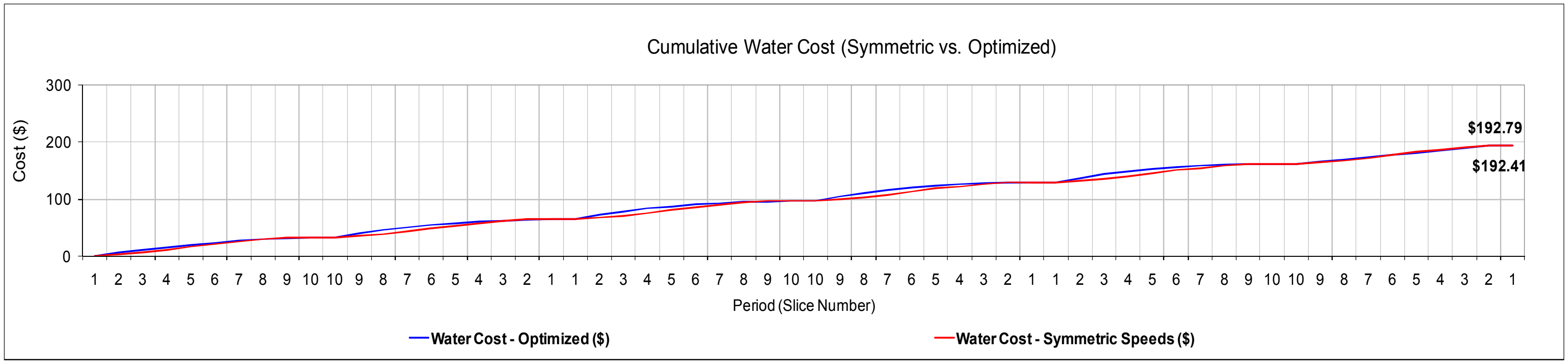


Fig. 11d. Comparison of cumulative water costs for the symmetric and optimized policies for bank #1, management zone 8

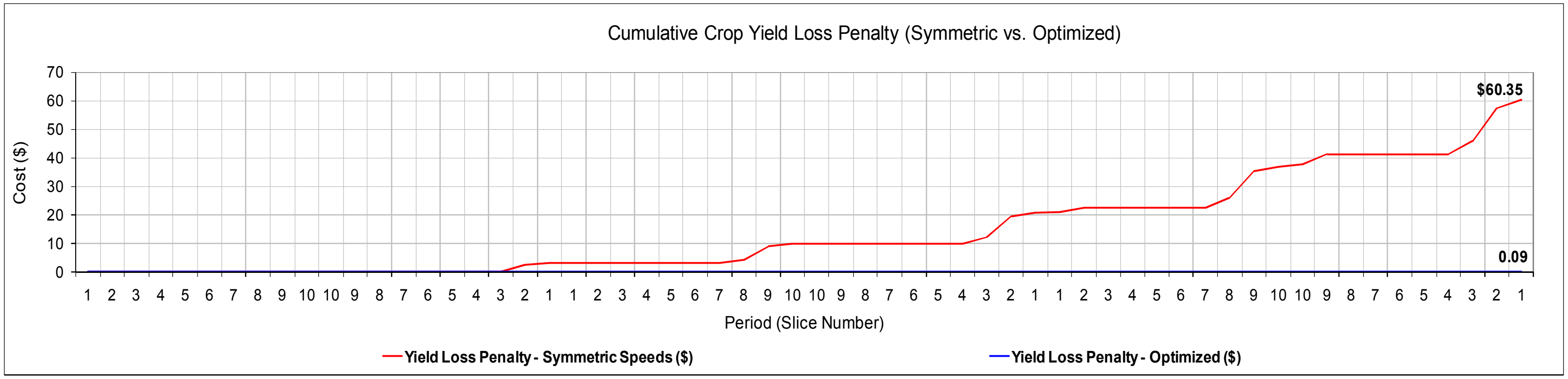


Fig. 11e. Comparison of crop yield losses for symmetric vs. optimized pivot speed prescriptions for bank #1, management zone 8

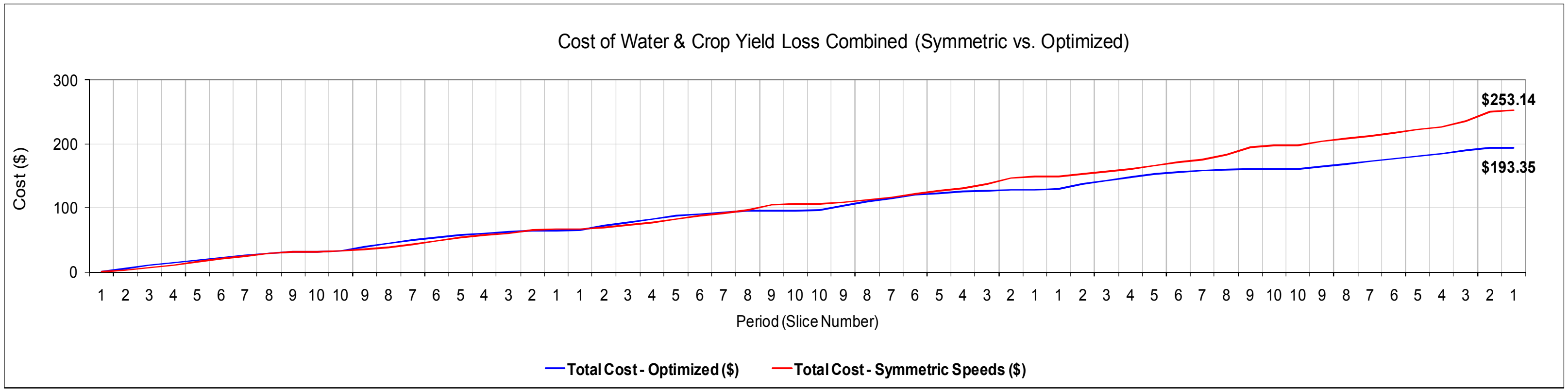


Fig. 11f. Comparison of total costs for symmetric vs. optimized pivot speed prescriptions for bank #1, management zone 8

Conclusions

The results of the simulations showed that the optimum speed prescription is, in principle, the one that applies water upfront in an amount that would be just enough to keep the moisture content above the critical depletion until the pivot comes back to the same location. This essentially requires the pivot to move slowly at the beginning of each sweep to release enough water to store enough water for evapotranspiration. The pivot then accelerates for the rest of the sweep and then slows down again at the beginning of the next sweep. Such a prescription maintains the moisture content above the critical depletion and prevents any yield losses. In all simulations, the optimum prescriptions as described above were significantly different than the prescription used prior to the simulation.

The results of the simulations also showed that the optimization results are sensitive to the initial moisture condition and whether the variations in the soil moisture content are around the field capacity or critical depletion. If the soil moisture content remains in the vicinity of field capacity, then no yield loss cost is incurred as expected and the only cost incurred is the irrigation water cost with any irrigation water in excess of the field capacity being wasted increasing the total cost. If the evapotranspiration rate is also much less than the irrigation rate, then the only cost that would incur would be due to the excess water lost to surface runoff or deep percolation Under such circumstances, the optimization effort would provide relatively less benefits for the farm management. However, if the soil moisture content is in the vicinity of critical depletion, significant cost increases were observed due to yield loss as the moisture content quickly falls below the critical depletion due to the water lost through evapotranspiration until the pivot comes back to the same location.

Finally, the optimization results also showed that the potential value of the optimization effort significantly depend on the cost of water and the crop. For example, if the irrigation water is obtained from wells with no consumption limits and for free, which is the case in some parts of the country, then the cost of irrigation water is mainly due to the fixed costs, such as electricity consumed during pumping. As such fixed costs typically incur independently of the amount of water pumped, the potential benefits of the proposed optimization model can be relatively limited. However, as the groundwater consumption is increasingly regulated particularly in the semi-arid and arid regions of the country, the proposed optimization model can provide significant value for the farm owners if the cost of the water is higher due to the imposed water consumption permitting requirements when the soil water content fluctuates around the field capacity. Similarly, the model can provide significant value for farm owners if the soil water content fluctuates around the critical depletion, particularly for fields with high value crops.

Evaluation of Work

While the center pivot simulation work provided useful insights as to the basic criteria needed for an optimal operation of a center pivot irrigation system, the simplifying assumptions underlying the described simulation model may result in significant errors under certain circumstances. For example, precipitation, which was ignored in the model, would significantly impact the soil water content and affect the center pivot flow rates in the optimal irrigation prescriptions proposed in this study. Although, precipitation data was collected for the field in this study, precipitation was beyond the scope of this study and its inclusion in the model was planned for further stages of the research project. Similarly, the water balance equation in this study consists of only evapotranspiration and irrigation in that all applied irrigation water remains in the system until it is lost due to evapotranspiration. This assumption inherently ignores the surface runoff and deep percolation, which can significantly affect the water balance equation if the topography has steep enough slopes to allow surface runoff and the soil layer underlying the root zone is porous enough to allow vertical flow of the applied irrigation water that penetrates through the root zone. The underlying assumption of constant root zone throughout the field is another limitation of the study, due to the spatial variability of plant root zones observed in nature. In the presence of precipitation, surface runoff, deep percolation and root zone as additional variables to the simulation model, more complex methods, such as numerical methods (e.g. finite element models) should be used that can incorporate the complex interactions of all the model parameters.

In spite of the above simplifying assumptions, the model provides a structure that can be extended by including the parameters ignored in this study. The additional parameters are not expected to change the optimization approach adopted in the model. However, addition of these additional parameters were not within the scope of this study at this stage.

CHAPTER IV

SOIL INFORMATION SYSTEM (SIS) IN PRECISION DRAINAGE DESIGN

Introduction

Although soil information has been used in increasing number of agricultural applications, soil information has been largely ignored in the drainage industry to date and drainage design tools currently available to drainage professionals do not incorporate soil information. Drainage contractors mainly rely on experience as their primary design aid and use the same drain depth and spacing in their installations for different soil series. (Atherton et al., 2004; Skaggs, personal communication, January 6, 2006; and Brown, personal communication, February 13, 2006). Based on a survey among drainage contractors in Ohio between 1995 and 1997, Atherton et al. (32004) reported that almost none of the drainage contractors used hydraulic conductivity information when designing a drainage system. These contractors also made little use of soil surveys and Ohio Drainage Guide. This widespread practice of using limited or no soil information brings about various risks in drainage design, mainly for the farm owners. For example, if the drain depth and spacing in the installation are over designed, farm owners are likely to incur unnecessary capital investment and maintenance costs. In the case of under design, there is a risk of crop yield loss, loss of credibility for the contractor, additional investment to eliminate any problems due to under design, such as wet areas that persist.

The second problem under this internship involved investigation of the feasibility and potential value of using STI's Soil Information System (SIS) in the design of precision drainage systems. At the outset, it was predicted that incorporating SIS into drainage design and construction could potentially yield a new software product or an opportunity for STI to provide new services for drainage design and construction. Because the objective was to create above-average return, such an investigation should also address strategic issues that may impact the profit potential of a new product or service, while evaluating the technical challenges that should be overcome before significant resources are allocated.

A major technical question that should be addressed was how can STI's precision soil maps can be integrated with drainage design and construction methods? Because STI's soil maps have a high spatial precision, their effective use in drainage design and construction requires drainage design methods and tools that can provide similar spatial precision capabilities. Another major technical question that should be addressed was how can soil physical properties obtained by SIS be used to predict soil hydraulic properties, such as hydraulic conductivity and soil water retention curve, which govern water movement in soil and, consequently, drainage system performance.

In order to address these questions, a two phase study was conducted in order to evaluate the feasibility of incorporating SIS into the drainage design process. In the first phase, the current drainage theory and design process, drainage design and construction methods and practices in the drainage industry were evaluated. As the departure point, a thorough literature survey was conducted to identify the existing body of knowledge and the principles of drainage theory and design were studied. The current drainage practices were investigated next. As part of this investigation, the current software tools used for drainage design were briefly evaluated. Because numerical methods constitute a significant portion of the drainage design literature and there are a number of numerical models that are used for drainage design, models based on numerical methods were also discussed. During the project, a number of prominent researchers were also interviewed in order to gain insight about the current research and gaps in drainage design and collect data for the study. These researchers were Dr. Wayne Skaggs from North Carolina State University, Dr. Richard Cook from University of Illinois and Dr. Bill Northcott from Michigan State University. The interviews were conducted by phone and each interview took about an hour. The intern also participated in an interview with the experts of CropTech Consultants, an Illinois based company, specializing in agricultural consulting services including drainage design and construction. In addition to the interviews with the researchers, the intern attended a two days training program presented by Ohio State University USDA Extension Program between 14-16 March 2006 as part of the project in order to have insights about the current industry practices between 14-16 March 2006. The training program included presentations given by USDA experts, university researchers and drainage contractors. The intern also conducted informal interviews with the representatives of the participating contractors, farm owners and USDA experts during this three days long training program.

In the second phase, the feasibility of incorporating STI's precision soil maps into drainage design process was investigated. This phase also includes an assessment of improving the estimation process of soil hydraulic properties, such as hydraulic conductivity, by the SIS, as accurate estimation of soil hydraulic properties is essential for improved design of drainage systems. Finally, because the ultimate goal of the project was to investigate the potential profitability of a new drainage design tool or service using STI's precision soil maps, a strategic analysis of the drainage design and construction industry was conducted from a competitive industry standpoint. The findings of these studies are summarized below.

Literature Review on Drainage Theory – Approximate Equations

Sizing, positioning and spacing of drainage laterals and mains require estimation of drainage volume that will drain from soil into these drainpipes and this, in turn, requires solution of subsurface flow equation. Solution to the subsurface flow equation with a free surface, which paved the way for drainage equations, dates back to 19th century when Dupuit solved the subsurface flow equation using Darcy's law based on the assumptions that a) the hydraulic gradient is equal to the slope of the water table and b) for small water-table gradients, the streamlines are horizontal and the equipotential lines are vertical (Kirkham, 1967). Dupuit-Forchheimer assumptions are summarized as follows (Hillel, 1998):

- The soil is uniform and of constant hydraulic conductivity,
- The drains are parallel and equally spaced,
- The hydraulic gradient at each point beneath the water table is equal to the slope of the water table above that point,
- Darcy's law applies,
- An impervious layer exists at a finite depth below the drain,
- The supply of water from above is at a constant flux q.

Further assumptions of conventional theory of prediction of water table response to drainage are that water table elevation directly over the drain is equal to the pressure head inside the drain, which further implies that head loss near the drain is relatively small and most of the flow above the water table in drained soils is vertical (Rogers et al., 1995). These assumptions rarely hold true in reality. It is also argued that Dupuit-Forchheimer assumptions underlying The Hooghoudt Equation may result in mass balance errors in drainage volumes (Ribbens and Garcia, 2002).

Based on Dupuit's flow equation and assumptions, The Hooghoudt proposed a drainage equation (Equation 4) which is still widely used by practitioners "to predict the height of the water table that will prevail under a given rainfall or irrigation regime when the conductivity of the soil and the depth and horizontal spacing of the drains are known" (Hillel, 1998).

$$S^2 = (4KH/q)\,(2d_a + H) \tag{4}$$

where S is the lateral spacing, K is the lateral hydraulic conductivity, H is the maximal height of the water table above the drain, d_a is the height of the drain above the impervious floor and q is the percolation flux at the soil surface due to rainfall or irrigation.

Empirical drainage design guidelines based on the above approximate equation together with local investigations and experience are provided to farm owners through recommendations in local drainage guidelines for specific soils in a particular area (Soil Conservation Service, 1973; Illinois Drainage Guide, 2006). However, such guidelines ignore spatial variations in soil properties at the field level, which can be significant, and, therefore, may result in suboptimal drainage design. For example, Schwab et al. (1982) found out that two drainage systems built in the same soil type can show significantly different behaviors and questioned whether soil type should be used as the only basis for drain spacing calculations (Atherton, 2004).

While the Hooghoudt equation above provides practical solutions for drainage design and has dominated the drainage literature for decades, one of its main weaknesses is that it assumes homogeneous and isotropic soil conditions ignoring the spatial variability of soil properties. For example, presence of profile layers of low conductivity can greatly retard drainage by affecting the flow pattern in the soil (Hillel, 1998), which may result in suboptimal drainage design. If spatial variability of soil hydraulic conductivity is incorporated into drainage design, such risks would be minimized or eliminated.

Existing Drainage Software

Based on their abilities and intended uses, it is concluded that the software evaluated in this study fall under two main categories: water table management software for yield maximization (Drainmod), and drainage system design software to layout drainage systems for a given topography and facilitate the tile installation process (Landrain and TilePro). These software are briefly discussed below.

Drainmod

Drainmod was developed in the early 1970s at North Carolina State University by Dr. Richard Skaggs, who is one of the leading researchers in the field of drainage. Drainmod has been accepted by the USDA Natural Resource Conservation Service for design and evaluation of drainage and subirrigation systems in humid regions (Skaggs, 1991) and has been extensively tested in water table management problems for different conditions.

Among the software evaluated in this study, Drainmod was the most comprehensive drainage simulation software. In Drainmod, "complex numerical methods are avoided by assuming steady state conditions for the soil water distribution above the water table," (Drainmod, 2005). It predicts water table depth using Hooghoudt equation. "Soil property inputs include the saturated hydraulic conductivity (by layers), the relationships between drainage volume and water table depth, and information concerning upward flux from the water table. The effective root zone depth as a function of time is also an input. Hourly precipitation and daily maximum and minimum temperatures are read from weather records and the water balance is conducted on an hour by hour basis. Summaries of the model predictions for hydrologic components such as rainfall, infiltration, drainage, ET, etc., are available on a daily, monthly or annual bases. The performance of a given system design or management alternative may be simulated for a long period of climatological record, say 20 to 40 years to consider the effects of the year by year and seasonal variability" (Drainmod, 2005).

While Drainmod is the most comprehensive software among the three evaluated in this study, its main drawback is that it allows only five soil layers and only one horizontal hydraulic conductivity can be assigned for each layer. The lateral hydraulic conductivities are assumed to be spatially constant. A single, depth averaged equivalent hydraulic conductivity is then used in the calculations for the entire profile (Skaggs, 1991, pp.214). Therefore, although Drainmod allows using five different vertical hydraulic conductivity values, because a single horizontal hydraulic conductivity can be used in the model, spatial variability of lateral hydraulic conductivity is inherently ignored.

Landrain

Landrain is a DOS-based drainage system design software. It was also developed in 1970s and is currently marketed by A B Consulting Co., Inc. based in Lincoln, Nebraska. Subsurface drainage design process with Landrain involves the following four phases: creation of a topography model; building the drainage system layout; computing depths and grades of the system; and determining capacity and pipe sizes

(Sands et al., 2000; Landrain, 2002). Landrain calculates the slopes and depths of the drainage system at which drainage pipes should be laid within the constraints (e.g. minimum and maximum slopes) provided by the user based on the topographical information. The drainage system is then forced to approximate the field topography where slope permits (Sands et al., 2001; Landrain, 2002). The pipe diameters are calculated using Manning's pipe flow equations based on the drainage coefficient (e.g. depth of water removed in 24 hours) set by the user. Landrain then calculates the material cost of drainage system pipes based on the calculated pipe cross sectional areas that can transmit the set flow rate using the pipe unit prices entered by the user.

Unlike Drainmod, Landrain does not use any soil information as it does not calculate drainage volumes. The user should estimate the subsurface drainage volume by using hydrology software or other methods (e.g. NRCS guidelines).

Tilepro

Tilepro is a Windows based drainage system design software developed by Delta Data Systems based in Picayune, MS. Similar to Landrain, Tilepro's basic function is to show the user how a proposed main and its associated laterals will lay under the ground (Tilepro User Documentation, 2002). Its main goal is to assist drainage design and installation professionals in laying out the proposed drainage system in the field. Unlike Landrain, because the software does not calculate and drain spacings or depths using any hydrological or drainage equations, the user should calculate these important design criteria by other means.

The plans and cross sections prepared by Tilepro can be used to ensure that minimum tile line depths are maintained as the topography changes. The user can place the drain tile lines within the permissible range of depth (i.e. the depth between the minimum depth above which the tile should not be laid and the maximum depth that a trencher can practically reach during the laying operation) using Tilepro's cross sectional plans. Unlike Landrain, it does not calculate the sizes of proposed drainpipes based on the flow rates. It also does not estimate pipe material costs. The main strength of Tilepro is that it is fully integrated with GIS and has the capability of reading and processing topographical data collected by GPS.

Numerical Models

Contrary to approximate equations, complexity of water movement in soil can be addressed more accurately using numerical methods. While approximate equations assume that subsurface flow occurs only within the saturated zone, numerical methods can handle flow both in saturated and unsaturated zones. Spatial variations in soil properties (e.g. anisotropy), changes in hydraulic conductivity as a function of saturation or head, different boundary conditions (e.g. streams or drains), sink (e.g. root water uptake) or source (e.g. irrigation) terms can be easily incorporated into the calculations due to the cell based approach of these methods. The mass balance equations, together with Darcy's equation, then can be solved iteratively for all the cells constituting the flow field to calculate the flow rate, head, etc. both temporally and spatially for variable soil properties.

Although there is no commercially available drainage design software that uses numerical methods, a number of models have been recently developed in the academia and more research is currently ongoing. These numerical models typically use three dimensional finite element schemes and can simulate both saturated and unsaturated flow. Recent numerical models (Buyuktas and Wallender, 2002; Buyuktas and Wallender, 2002; USDA Products and Services, SWMS-3D) provide comprehensive simulation tools that can incorporate various agricultural processes, such as irrigation, evaporation, transpiration, soil water extraction by roots with vadose zone, groundwater flow and transport mechanism, as well as drainage, in order to manage water table and nitrate release. These models can model flow fields "composed of non-uniform soils having an arbitrary degree of local anisotropy. The water flow part of the model can deal with prescribed head and flux boundaries, as well as boundaries controlled by atmospheric conditions" (USDA Products and Services website, January 06, 2006). The flow equation incorporates a sink term to account for water uptake by plant roots and can handle flow regions delineated by irregular boundaries, such as drain tiles.

Comparison of Approximate Equations and Numerical Methods for Drainage Design

While exact flow equations and numerical methods were not used in early drainage design software, such as Drainmod, due to computational limitations (Skaggs, 1991), they are still mainly limited to academic research projects. Unlike in other fields, such as environmental remediation, currently no commercially available drainage design software exists that uses numerical methods in drainage modeling and design.

Despite the higher accuracy of numerical models, during the interviews conducted, the leading researchers in the field of drainage design raised doubts about commercial viability of numerical methods as a tool in drainage design. According to Dr. Skaggs, although unsaturated flow, as well as saturated flow, can also be modeled with numerical models and potentially more accurate results can be obtained, justification of the costs associated with numerical models given the benefit remains a question and should be analyzed carefully. These costs include increased development costs, increased soil data collection cost and increased costs associated with interpreting and applying the results of a numerical model. While these costs may be justified for some problems in other fields, such as groundwater remediation, their justification for agricultural drainage should be carefully investigated. Similarly, numerical models are too costly and time consuming, require too much computing power, and require more data than can be collected economically. In return, there is only 3-4% improvement in the crop yield increase obtained by the efficiency of the installed drainage system (Dr. Cooke, personal communication).

Estimation of Soil Hydraulic Properties Using SIS

Although drainage design models have become increasingly sophisticated, accuracy of these models still heavily rely on the hydraulic conductivity estimate used in the model (Skaggs, personal communication, January 6, 2006; Cooke, personal communication, February 6, 2006). Improving hydraulic conductivity estimates can benefit drainage design professionals and farm owners alike by improving drainage system performance and return on investment. For example, Merva (1995) showed that when the true hydraulic conductivity is only three times the estimated value, the apparently optimum spacing can reduce almost by half, resulting in over designed drainage systems. Similarly, when the hydraulic conductivity is over estimated, there is a risk of under design, which can reduce crop yield and, therefore, net benefit of the drainage system.

Estimation of hydraulic conductivity using SIS is the most crucial step in incorporating SIS into drainage design. Although approximate and numerical subsurface flow models have become more and more sophisticated, their success still critically depends on the accuracy of the estimated soil hydraulic properties. Mohanty et al. (1998) report that saturated hydraulic conductivities estimated both by field and laboratory methods can be significantly different for the same soil and these differences can significantly affect tile flow predictions when numerical models are used. In order to determine the impact of input parameter uncertainty on Drainmod results, Haan and Skaggs (2003) and Sabbagh and Fox (1999) conducted field studies to investigate the impact of various input design parameters on the results obtained by Drainmod. These studies showed that the large standard deviations of the hydraulic conductivity field measurements result in higher uncertainty in the model predictions. According to Haan and Skaggs (2003), reducing the uncertainty in the model parameters, in particular hydraulic conductivity, can reduce the uncertainty in the model outputs. In an attempt to reduce this uncertainty, Northcott (personal communication, February 15, 2006) reported that a modeling study is currently underway to divide the field into management zones of homogeneous hydraulic conductivities and run Drainmod iteratively with more accurate input parameters for each zone. Using SIS precision soil maps that incorporate spatial hydraulic conductivity in the drainage design would significantly reduce the uncertainty associated with hydraulic conductivity and contribute to modeling efforts to improve drainage design.

The most critical soil hydraulic property is the saturated hydraulic conductivity as most of the subsurface flow takes place in the saturated zone (Rawls et al., 1998). This is particularly true for Drainage models such as Drainmod that assume the subsurface flow takes places only in the saturated zone. On the other hand, when subsurface flow is modeled in both saturated and unsaturated zones, as in the case of numerical models, unsaturated hydraulic conductivity should be known as a function of moisture content. SIS, in combination with the Soil Imaging Penetrometer (SIP), has the potential to estimate both saturated and unsaturated hydraulic conductivities, as well as other soil hydraulic properties such as soil water retention curve. Images obtained with the SIP provide information about the pore size distribution of the soil, which can be used to estimate the water retention curve, as the water retention curve is essentially represents the pore size distribution of soil. The soil water retention curve then can be used to estimate the unsaturated hydraulic conductivity, as unsaturated conductivity is a function of soil water retention curve. Estimation of soil hydraulic properties using soil images remains to be an active area of research. STI is currently conducting a research project to estimate the soil water characteristics curve using SIS and SIP.

Strategic Analysis of the Drainage Industry Environment and Use of SIS as a Competitive Advantage in Drainage Design and Construction

Porter (1980) defines five forces that jointly determine the intensity of industry competition and profitability for product and service based industries. These forces are i) customers, ii) suppliers, iii) substitutes, iv) potential entrants, and v) industry competitors. These forces can all increase the competitive pressure for a new product or service. The competitive advantage of a product or service then depends on how a business entity positions itself with its product or service against these forces or how it can influence them in its favor (Porter, 1980).

Five forces defined by Porter (1980) may also determine the success of a new drainage design tool or service provided by the STI. For example, who are the major competitors currently providing similar services in drainage design and construction? Even if there are currently no major competitors, the threat of new entrants that may provide similar products or services could also significantly diminish the profit potential for STI. Are there any potential new entrants that can provide similar products and services in the drainage industry? On the other hand, even if STI successfully develops a better product or service that can significantly improve drainage design and construction without any competition, lower cost substitutes may still undermine the profit potential of a superior drainage design product or service. What lower cost options do the potential customers (e.g. farm owners) have to design and construct their drainage systems as a lower cost substitute for a superior product or service that STI may provide? Similarly bargaining power of the potential customers can reduce the profitability of a new drainage design tool or service. For example, Porter (1980) argues that if a customer has lower earning profits, poses a credible threat of backward integration, faces few switching costs, or if the industry product is unimportant to the quality of the buyers' products or services, the customer's bargaining power against the product or service provider can significantly increase, again undermining the profit potential. Where does a new drainage design product or service stand in the drainage industry in terms of the potential customers' bargaining power? Finally, suppliers can also impact the profit potential of a new product or service if the industry is dominated by a few suppliers and is more concentrated than the industry it sells to, the suppliers' product is an important input to the buyer's business or the supplier group poses a credible threat of forward integration (Porter, 1980). If drainage pipe manufacturers and drainage contractors are assumed to be the major suppliers in the industry, what is the potential power of these suppliers and how can they impact the profit potential of a new drainage design product or service?

In order to address these questions, drainage industry stakeholders and their positions in the industry environment were investigated with the objective of assessing the competitive power of each stakeholder with respect to the other(s). This assessment was then used to evaluate the commercial viability of a possible drainage design tool or service in the current drainage design and construction market.

Current Drainage Industry Environment

Industry environment strongly influences the competitiveness of a new service or product and determines the strategies potentially available to the firm (Porter, 1980). In the drainage industry, there are already well established players, who continue to shape the industry environment. Therefore, understanding their roles and their relationships with the industry environment is essential in order to formulate the right strategy for the introduction of a new service or product. According to Porter (1980), the state of competition in an industry depends on five basic competitive forces as shown in Figure 12.

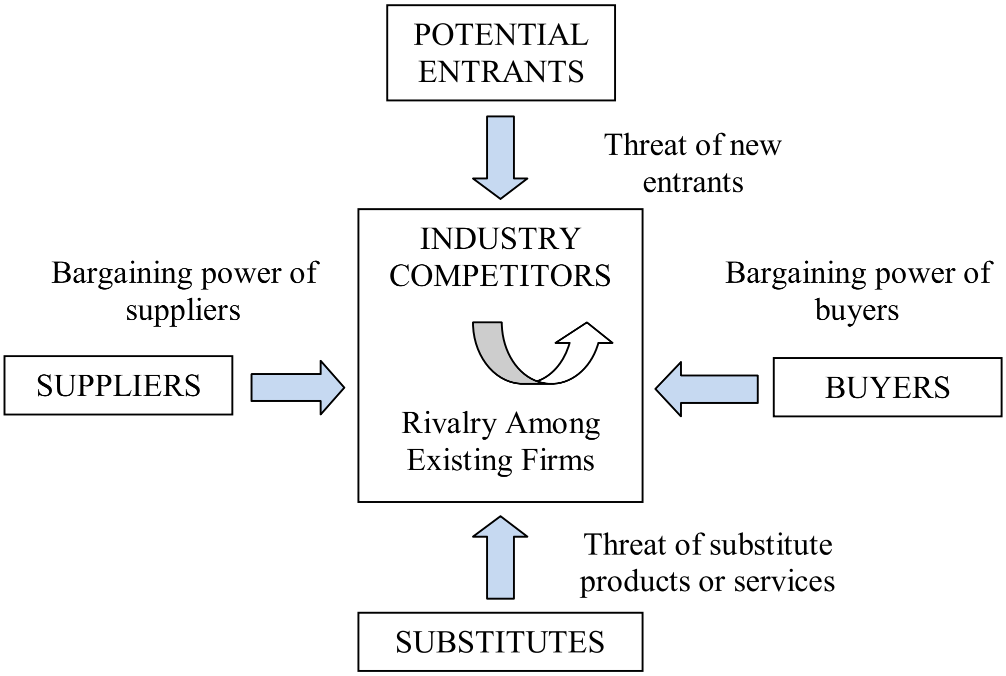


Fig. 12. Porter's Five Forces Model (After Porter, 1980)

While better drainage modeling tools using better hydraulic conductivity estimates would certainly improve the drainage system design, the demand for tools to achieve this goal in the current drainage industry environment requires a thorough analysis. In spite of the apparent risks of suboptimal design, the literature review, interviews with five university researchers in the field of drainage design, representatives of a private crop consultant company and two drainage contractors during the drainage school attended in Ohio indicated that the farm owners and drainage contractors are content with the current practices. As pointed out by a number of researchers during the interviews, lack of field research on effectiveness of drainage systems may be preventing farm owners from identifying the potential benefits of optimal drainage design. The following assessment can be made for the current drainage industry environment when it is analyzed using Porter's five forces model:

Customers

In a competitive market, buyers compete with the industry by requiring higher quality services at lower cost and play the competitors against each other (Porter, 1980). According to Porter (1980), among others, a customer group is powerful if:

- the products it purchases from the industry are standard or undifferentiated,
- the customer group earns low profits,
- poses a credible threat of backward integration,
- the industry's product is unimportant to the quality of the buyers' products or services.

Standard or Undifferentiated Products: The customers for drainage systems are mainly the farm owners and managers. Farm owners and managers install subsurface drainage systems in order to remove the excess water stress that reduces crop productivity. However, unless a problem becomes obvious after a subsurface drainage system is installed, such as wet areas, any drainage system, whether optimal or not, is typically accompanied by a yield increase. Due to the lack of widely accepted evidence supporting differentiated drainage design methods as a means to increase crop yield and quality, farm owners and managers may not perceive a strong need to utilize differentiated drainage design methods, which increases the bargaining power of farm owners and managers.

Low Profits: “Low profits create great incentives to lower purchasing costs” (Porter, 1980). The agricultural industry is typically known as an industry with low profit margins, which causes the farm owners or managers to be price sensitive when seeking services.

Threat of Backward Integration: “If customers either are partially integrated or pose a credible threat of backward integration, they are in a position to demand bargaining concessions” (Porter, 1980). One indication of the increasing interest among farmers in drainage system design and installation is the increasing number of farm owners and managers who attend the training programs in this area. At the four days training program presented by the Ohio State University USDA Extension Drainage School, of the 39 participants 8 participants were farm owners or managers. It was also learned that the previous year as many as one third of the participants were farm owners or managers. The farmers attending the school also confirmed that there is a growing interest among farm owners and managers in installing their own drainage systems or becoming drainage contractors, partially due to contractors’ backlog of drainage system installation work in the Midwest. As an alternative, low cost drainage system installation equipment allow farmers to install their own systems with little training or expertise. For example, drainage systems can be installed by pull behind plows by the farm owners and managers relatively easily at a cost significantly lower than what the drainage contractors charge. Although the data obtained for this study through the interviews with academia and industry practitioners represent only a part of the industry in the Midwest and, therefore, should be interpreted with caution, it appears that the farm owners' and managers' ability to install their own drainage systems and the growing interest among the farm owners and managers to install drainage systems commercially increases the power of farm owners and managers (i.e. customers).

Product's Importance to the Quality of the Customer's Products: "When the quality of the customers' products is very much affected by the industry's product, customers are generally less price sensitive" (Porter, 1980). Although it is widely known that eliminating the excess water stress increases the crop yield, as mentioned earlier, there is limited research conducted on the relationships between the overdesigned or under designed subsurface drainage systems installed to date and the accompanied crop yield increase. This lack of evidence undermines the importance of high quality drainage systems to the quality and, to a certain extent, the quantity of the crop yields in the eyes of farm owners and managers. This, in turn, increases the power of farm owners and managers when they consider alternative methods to design and install their drainage systems.

Suppliers

“Suppliers can exert bargaining power over participants in an industry by threatening to raise prices or reduce the quality of purchased goods and services” (Porter, 1980). According to Porter (1980), among others, a supplier group is powerful if:

- the supplier group is dominated by a few companies and is more concentrated than the industry it sells to,
- the supplier group is not obliged to contend with other substitute products,
- the suppliers’ product is an important input to the buyers’ business,
- the supplier group poses a credible threat of forward integration.

Concentration of Suppliers: Main suppliers in the drainage industry are the contractors and pipe manufacturers, who have significant bargaining power. The researchers and the industry professionals interviewed in 2006 stated that the drainage contractors in Midwest had typically months long backlog due to the increasing demand from the farm owners and managers.

Substitutes for the Suppliers’ Products: Currently there are no substitutes for the subsurface drainage tiles, which gives significant power to the tile manufacturing companies. However, the services provided by the drainage contractors have been increasingly substituted by those farmers who choose to install their own drainage systems or enter the drainage system installation business, which decreases the bargaining power of the drainage contractors.

Forward Integration: Most drainage contractors and some of the tile manufacturing companies have vertically integrated by providing design services in addition to installation. The representatives of one crop consultant company in Illinois and some drainage contractors in Overholt Drainage School in Ohio stated that drainage contractors typically determine the design of the drainage system based on experience and these designs typically put the ease and speed of installation ahead of other considerations, apparently because of work backlog. During these personal communications, these practitioners also indicated that there were occasions that drainage contractors refused to implement drainage system designs prepared by others, which created installation difficulties for the contractors.

Substitutes

Although there is no substitute for a subsurface drainage system for the farm owners and managers, based on the interviews conducted for this study there appears to be a trend that increasing numbers of farm owners and managers are installing their own subsurface drainage systems.

Potential Entrants – Threat of Entry

“Threat of entry into an industry depends on the barriers to entry that are present, coupled with the reaction from existing competitors that the entrant can expect” (Porter, 1980). In the context of Porter’s Five Forces model, consulting firms who can provide agricultural drainage design services are potential entrants in this industry. However, the high demand for drainage contractors and the vertical integration of drainage contractors by providing drainage design potentially hinders development of new precision drainage system design methods. A new entrant into this market may face a difficult time in getting comparable prices, may face retaliation and become squeezed if vertically integrated drainage contractors offer different terms for designs made by new entrants (Porter, 1980).

“Another barrier to entry is the presence of switching costs, that is, one-time costs facing the buyer of switching from one supplier’s product to another’s” (Porter, 1980). According to Porter (1980), cost and time to test a new service, need for technical help as a result of reliance on seller’s technical expertise, and even psychic costs of severing a relationship can make switching from one supplier to another costly for the customer. Porter (1980) further states that “if these switching costs are high, then new entrants must offer a major improvement in cost or performance in order for the buyer to switch from an incumbent.” If farm owners or managers substitute the drainage designs currently provided by contractors and tile manufacturers by those that can be potentially provided by consultants, they would have to rely on the expertise of such consultants and possibly complex design processes, such as precision drainage designs based on spatial soil information. This reliance may bring about uncertain cost estimations for the farm owners or managers as a potential cost of switching. Furthermore, outsourcing the drainage design to consultants can severe the relationships between farm owners and managers and drainage contractors, again acting as a potential cost of switching.

In addition to the above barriers of entry, established firms may have cost advantages not replicable by potential entrants. These cost advantages include favorable locations and learning or experience curve (Porter, 1980). Because most farm owners and managers hire local drainage contractors, drainage contractors are favorably located to win the drainage design business of farm owners and managers unless drainage design consultants can serve these customers in their local areas. Furthermore, because contractors have typically hands on experience with the installation of drainage systems, which potential drainage design consultants would likely to lack, experience serves as a cost advantage for the contractors.

Another barrier for the entrants into an existing market is the entry deterring price, which “balances the potential rewards from entry forecast by the potential entrant with the expected costs of overcoming structural entry barriers and risking retaliation” given the prevailing existing price structure (Porter, 1980). A potential entrant should price its product or service below this hypothetical entry deterring price in order to earn above above-average profits in the long term. A new service or product with a price above the entry deterring price is likely to be short-lived in the face of competition from the existing competitors who provide prices at or below the entry deterring price.

Another risk that drainage consulting companies face, including STI, is the typically high overheads that consulting firms incur when providing services. Because consulting firms typically employ highly qualified employees (e.g. employees with M.S. or Ph.D. degrees), their costs are typically higher. Furthermore, they may also charge a premium in their rates that reflect the know-how they develop in-house, often at a cost born by the company, when providing their services. On the other hand, drainage contractors typically provide low cost drainage design services based on simplified drainage design guidelines or experience using an off-the-shelf drainage software and they incur relatively lower costs when providing drainage design services. Therefore, the overhead costs and premiums charged by the consulting firms typically make it difficult for them to match the entry deterring price. As mentioned earlier, the entry deterring price barrier is exacerbated by the fact that unless a problem becomes obvious after a subsurface drainage system is installed, such as wet areas, optimality or effectiveness of the design methods employed and the drainage systems installed by the contractors is uncertain since any drainage system, whether optimal or not, is typically accompanied by a yield increase. Therefore, demonstrating the value of a precision drainage system in comparison with the traditional methods remains to be a challenge. More research should be conducted on the effectiveness of the installed subsurface drainage systems to date installed by the contractors to determine the value of precision drainage design services with respect to the entry deterring price.

Another major player in the drainage industry is the tile manufacturers, who have considerable power mainly due to the consolidation of the tile manufacturers in recent years. One example for this consolidation is the acquisition of Hancor Company in 2005 by ADS Company, which is currently regarded as the biggest tile manufacturing company in the Midwest. During personal communications with the practitioners, some practitioners indicated that a tile manufacturer sells tiles directly to contractors and do not provide services directly to the farm owners and managers. The same practitioners also indicated that another tile manufacturing company provides services directly to farmers after it acquired a contractor company through vertical integration. They also added that at least one tile manufacturing company now provides drainage design services as well. Because of the consolidation in the tile manufacturing industry and the possibility of tile manufacturing companies to vertically integrate to provide installation services, tile manufacturers provide a potential entry threat for the existing drainage contractors.

Industry Competitors

Industrial competition occurs one or more competitors feels the pressure of tactics employed by the competitors, such as price competition, advertising battles, product introductions, and increased customer service or warranties (Porter, 1980). Because the drainage design services segment of the agricultural industry has not yet matured, the competition is nearly non-existent currently. However, this is expected to change in the future due to the increasing research on effectiveness of drainage design on crop yield as well as the regulatory requirements aimed to limit agricultural discharges into the water bodies.

Evaluation of Work

This study focused on soils with relatively high water table and maximization of yield by eliminating excess water stress. Midwest drainage practices are a typical example for using drainage systems for yield maximization by eliminating excess water stress. In irrigated arid regions additional stresses may be caused by salinity and drainage may also be used to reduce those stresses for yield maximization (Skaggs, 1992). Further research is needed to investigate drainage systems in order to extend the conclusions of this study for arid and other regions.

The focus of this research has been mainly the farm owners, tile contractors, and regulatory agencies, who are the three major stakeholders in the US drainage industry. The conclusions and proposed recommendations are based on the US drainage industry and regulatory environments. Outside the US different stakeholders (e.g. governments, international financial institutions such as World Bank) and political environments can have significant influence on drainage practices and may provide additional opportunities.

The industry analysis using Porter's Five Forces model indicates that although there is a potential market for improved drainage design products or services, the current dynamics of the industry may limit their marketability to the end users (e.g. farm owners and contractors). The drainage industry appears to be fragmented. Although a new drainage design product or service provided by consulting companies can be initially costly for the agricultural end users, this entry barrier can be overcome by benefits of scale economies. This would require large companies to endorse such new products or services and invest in them. It also appears that the benefits of the optimal drainage design in terms of yield increases should be documented and communicated with the farm owners more effectively, before a viable customer group can be created. Finally, the regulatory changes expected in the industry to curb the non-point pollution of the country's water bodies due to agricultural contaminants released from overdesigned subsurface drainage systems provides a unique opportunity to develop and market innovative drainage design tools and service. The intern has observed that preparations among the regulatory agencies, academia and some practitioners are already underway (e.g. Agricultural Drainage Management Systems (ADMS) working group) to define the means of such regulations that should be imposed on the drainage practice.

CHAPTER V

ASSESSING SOIL SALINITY USING IN-SITU RESISTIVITY MEASUREMENTS

Introduction

High soil salinity remains to be a major concern in agriculture because salts in the agricultural irrigation water tend to accumulate in the soil and reduce the soil's productivity over time. Because soil salinity can affect crop yield significantly, its accurate assessment is an essential part of farm management in order to address solution methods (e.g. flushing the soil with water to drain away the salts). Although laboratory methods provide an accurate way to assess soil salinity, these methods are often time consuming and expensive. Therefore, significant research has been conducted to assess soil salinity through indirect methods. One such method is the measurement of electrical conductivity of the soil using geophysical methods, which then can be used to assess the soil salinity as the electrical conductivity is greatly enhanced due to the conductance of salt accumulated in the soil. Because soil resistivity measurements are obtained by the SIS during field mapping in a cost effective and fast manner, assessment of soil salinity using the SIS resistivity measurements potentially offers a great value for practitioners.

In order to test a soil salinity assessment methodology, the electrical conductivity predictions based on field measurements should be validated by "true" electrical conductivity values obtained under laboratory conditions using an appropriate relationship. Under laboratory conditions, soil salinity is often defined in terms of the electrical conductivity of the saturated soil paste extract (EC_e), as measuring the electrical conductivity at typical field water contents (EC_w) can be a challenge for practical purposes (Corwin and Lesch, 2003). On the other hand, at the field scale electrical conductivity is typically measured in terms of apparent soil electrical conductivity (EC_a), which lumps the conductivities in solid and water phases. Accordingly, Rhoades et al. (1989) provide the following relationship between field and laboratory conductivity measurements:

$$EC_a = \left[\frac{(\theta_s+\theta_{ws})^2 \, x \, EC_w \, x \, EC_s}{(\theta_s \, x \, EC_w)+(\theta_{ws} \, x \, EC_s)}\right] + (\theta_w - \theta_{ws}) x \, EC_w \qquad (5)$$

where θ_w is the volumetric moisture content, EC_e is electrical conductivity of the soil paste extract, EC_w is the electrical conductivity of the soil solution, EC_s is the electrical conductivity of the indurated soil phase, θ_{ws} is the volumetric water content in the soil water pathway, θ_s is the volumetric content of indurated solid phase. Rhoades et al. (1989) and Corwin and lesch (2003) also provide the following relationships:

$$\Theta_w = \theta_g \text{ x } (\rho_b/100) \qquad (6)$$

$$EC_w = (EC_e \text{ x } \rho_b \text{ x } SP) / (100 \text{ x } \theta_w) \qquad (7)$$

$$\Theta_s = \rho_b / 2.65 \tag{8}$$

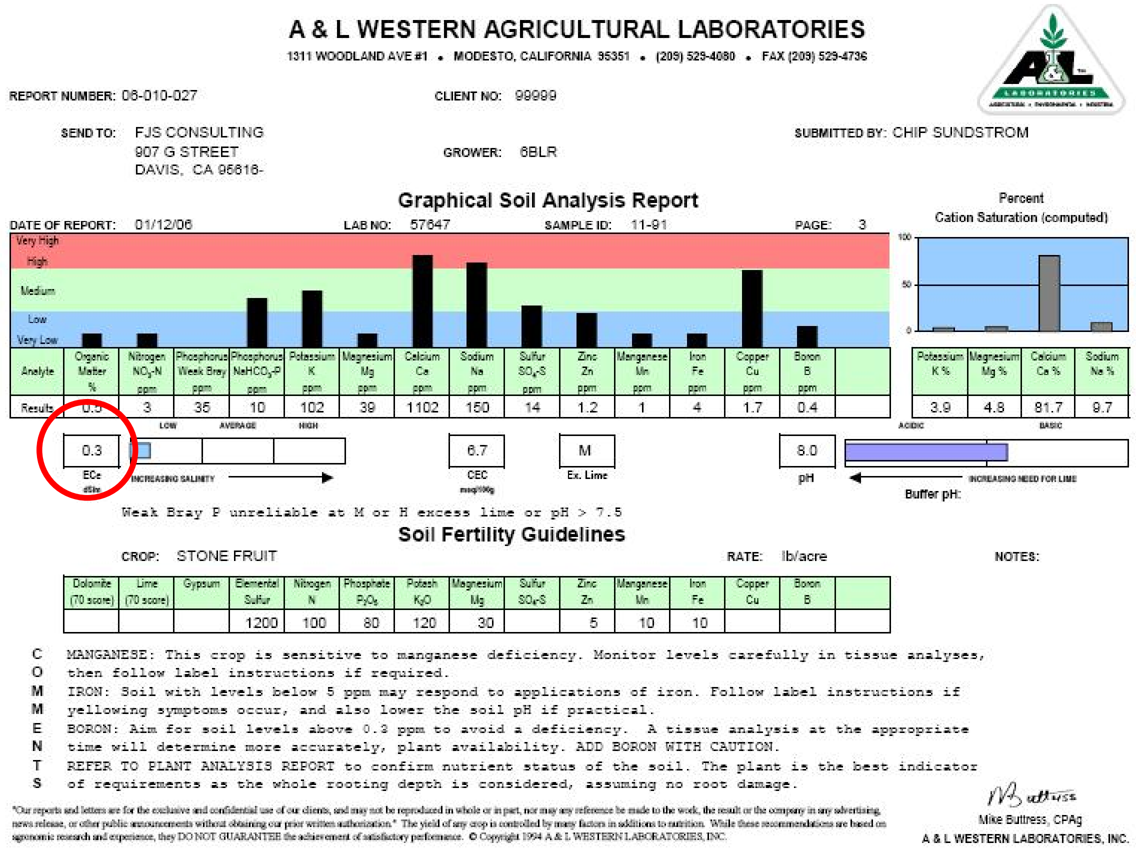
$$\Theta_{ws} = 0.639 \times \theta_w \times 0.011 \tag{9}$$

$$EC_s = 0.019 \times SP - 0.434 \tag{10}$$

where ρ_b is the bulk density and SP is the saturation percentage. Because the apparent electrical conductivity is the reciprocal of the electrical resistivity (R), i.e. $R = 1 / EC_a$ (Rhoades et al., 1999), by using field measured EC_a through resistivity measurements and Equations (5) through (10), EC_e values can be predicted and compared to those obtained by laboratory measurements for validation.

While the soil salinity assessment model described in Equations (5) through (10) have been tested successfully for resistivity measurements using methods such as electrical resistivity (i.e. Wenner array), electromagnetic induction (EM) and time domain reflectometry (TDR), which are near or above surface methods, to the best of STI's knowledge, the model has not been tested for resistivity measurements taken in the soil continuously as the probe goes into the soil using resistivity sensors.

The third problem that was investigated as part of this internship was the assessment of soil salinity using the electrical resistivity sensor measurements obtained by STI's soil probes in the soil using the soil salinity assessment model proposed by Rhoades et al.(1989). The objective of this analysis was to estimate the soil extract paste electrical conductivity (EC_e) values using resistivity measurements and compare them with EC_e values measured in the laboratory. Although STI's innovative soil probes were not designed to assess soil salinity, the resistivity values obtained in the vertical can potentially be used to assess the electrical conductance as resistivity is inversely proportional to resistivity. Therefore, assessment of electrical conductance using easily obtained resistivity values collected by the SIS could potentially provide a cost effective and fast method to assess soil salinity, if a reliable correlation can be established between the electrical conductance values estimated by the resistivity measurements of SIS and the electrical conductance values measured in the laboratory for the same soil.



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1311 WOODLAND AVE #1 • MODESTO, CALIFORNIA 95351 • (209) 529-4080 • FAX (209) 529-4736

REPORT NUMBER: 06-010-027
CLIENT NO: 99999

SEND TO: FJS CONSULTING
907 G STREET
DAVIS, CA 95616-

GROWER: 6BLR
SUBMITTED BY: CHIP SUNDSTROM

Graphical Soil Analysis Report

DATE OF REPORT: 01/12/06
LAB NO: 57647
SAMPLE ID: 11-91
PAGE: 3

Analyte	Organic Matter %	Nitrogen NO_3-N ppm	Phosphorus Weak Bray ppm	Phosphorus $NaHCO_3$-P ppm	Potassium K ppm	Magnesium Mg ppm	Calcium Ca ppm	Sodium Na ppm	Sulfur SO_4-S ppm	Zinc Zn ppm	Manganese Mn ppm	Iron Fe ppm	Copper Cu ppm	Boron B ppm	
Results	0.5	3	35	10	102	39	1102	150	14	1.2	1	4	1.7	0.4	

Percent
Cation Saturation (computed)

Potassium K %	Magnesium Mg %	Calcium Ca %	Sodium Na %
3.9	4.8	81.7	9.7

0.3
ECe
dS/m

6.7
CEC
meq/100g

M
Ex. Lime

8.0
pH

Buffer pH:

Weak Bray P unreliable at M or H excess lime or pH > 7.5

Soil Fertility Guidelines

CROP: STONE FRUIT
RATE: lb/acre
NOTES:

Dolomite (70 score)	Lime (70 score)	Gypsum	Elemental Sulfur	Nitrogen N	Phosphate P_2O_5	Potash K_2O	Magnesium Mg	Sulfur SO_4-S	Zinc Zn	Manganese Mn	Iron Fe	Copper Cu	Boron B	
			1200	100	80	120	30		5	10	10			

C
O
M
M
E
N
T
S

MANGANESE: This crop is sensitive to manganese deficiency. Monitor levels carefully in tissue analyses, then follow label instructions if required.
IRON: Soil with levels below 5 ppm may respond to applications of iron. Follow label instructions if yellowing symptoms occur, and also lower the soil pH if practical.
BORON: Aim for soil levels above 0.3 ppm to avoid a deficiency. A tissue analysis at the appropriate time will determine more accurately, plant availability. ADD BORON WITH CAUTION.
REFER TO PLANT ANALYSIS REPORT to confirm nutrient status of the soil. The plant is the best indicator of requirements as the whole rooting depth is considered, assuming no root damage.

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M Buttress
Mike Buttress, CPAg
A & L WESTERN LABORATORIES, INC.

Fig. 13. Sample laboratory measurement report showing soil ECe value

In the last project, the comparison between the estimated and measured electrical conductance values was performed by standard statistical correlation analysis. Data (e.g. resistivity values) obtained from one of the fields mapped by STI were used for demonstration purposes, while laboratory measurements for soil samples collected from the same field were used for verification of the SIS based estimates. A sample laboratory report of a soil sample showing the measured EC_e values is shown in Figure 13.

Estimation of EC_e Using SIS Resistivity Measurements for a Test Site

The salinity prediction capability of SIS diver resistivity data was analyzed using the SIS diver data obtained for one of the site mapped by STI and laboratory data obtained for soil samples from the same site. The analysis was conducted by estimating EC_e values with the model proposed by Lesch and Corwin (2003) using Equations 5 through 10 and comparing them with the "true" EC_e values obtained in the lab. Because the Equations 5 through 10 are derived for a reference temperature of 26.815 C and the conductivity of the soil is dependent on soil temperature, the estimates should be corrected for the actual temperature of soil at the time of the field measurements. The last step involved correcting the EC_e values for the temperature correction as described by Lesch and Corwin (2003) using Equations 11 and 12.

$$f_t = 0.4470 + 1.4034^{e-\{t/26.815\}} \tag{11}$$

$$EC_a = f_t \,.\, EC_t \tag{12}$$

Results

In the first step of the analysis, the resistivity values obtained from SIS diver measurements were used to estimate EC_e values. The analysis of the resistivity measurements was conducted only for the locations at which both laboratory and SIS diver measurements were obtained. Unlike SIS diver measurements, laboratory measurements of EC_e are average values obtained over a length of soil core (e.g. 50 cm). Because the SIS diver provides continuous resistivity measurements for the soil depth measured, a discrete EC_e value was estimated for every resistivity measurement obtained from the diver. In the first step of the analysis, these discrete EC_e values were plotted over the depth of soil measured and compared with the laboratory measurement obtained over the same depth of soil. Some of the results of this comparison are shown in Figures 14 through 17.

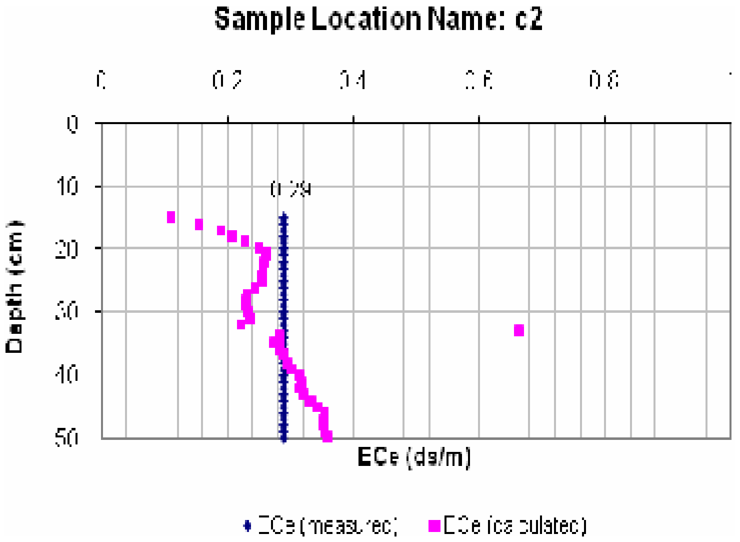

Fig. 14. Sample plot of measured vs. estimated EC_e values for the top 50 cm of soil at location c2

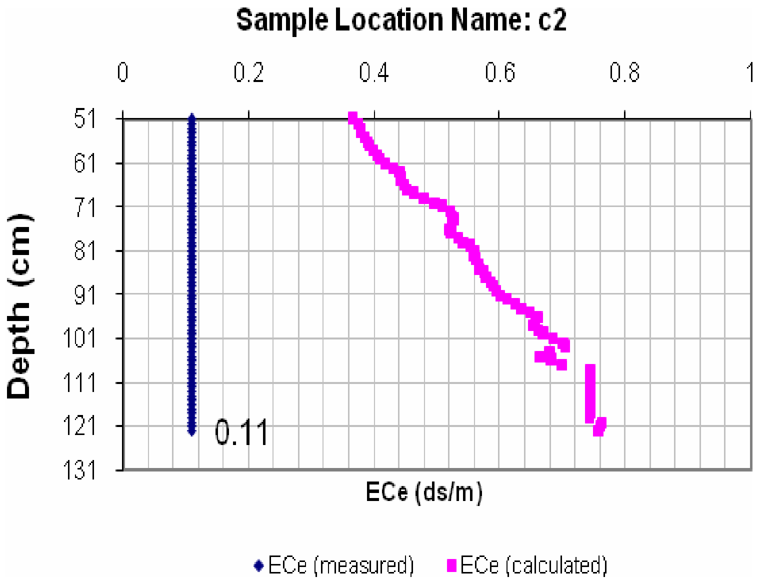

Fig. 15. Sample plot of measured vs. estimated EC_e values for the lower soil section at location c2

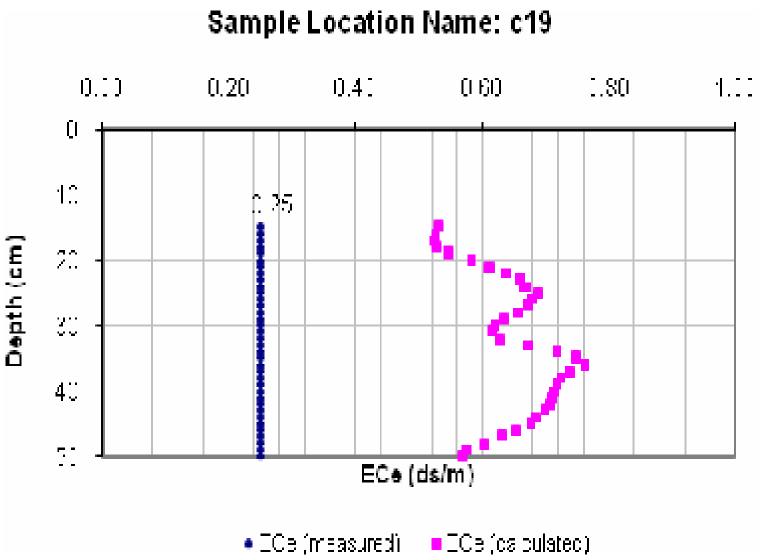

Fig. 16. Sample plot of measured vs. estimated EC$_e$ values for the top 50 cm of soil at location c19

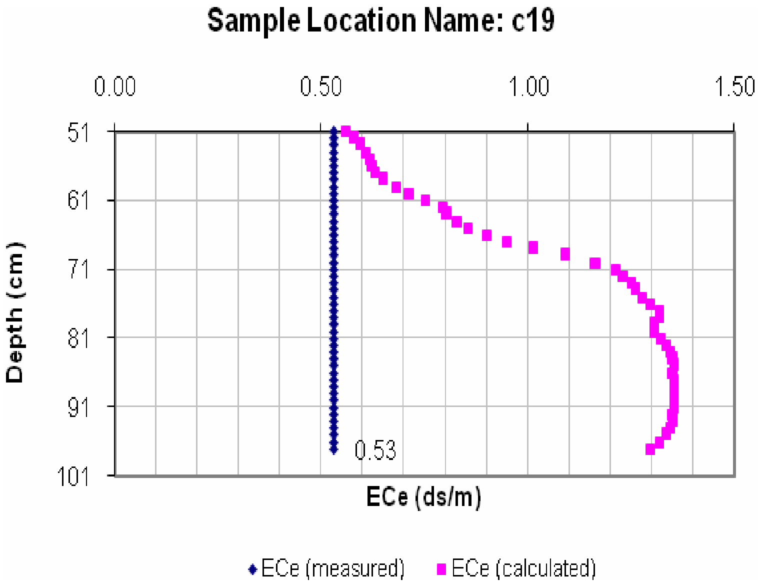

Fig. 17. Sample plot of measured vs. estimated EC$_e$ values for the lower soil section at location c19

A visual inspection of the plots for measured and estimated EC_e values showed no clear relationship between the measured and estimated EC_e values. In the next step, a correlation analysis was conducted for all EC_e pairs in order to assess the relationship between the measured and estimated EC_e values for all the available data. The correlation analysis was conducted for the top 50 cm and for the remainder of the soil depth over which the EC_e values were estimated. In total 33 EC_e pairs were included for each correlation analysis. The limited number of the pairs was due to the limited number of laboratory measurements available. The results of the correlation analyses for the top and bottom portions of the soil are shown in Figure 18 and 19.

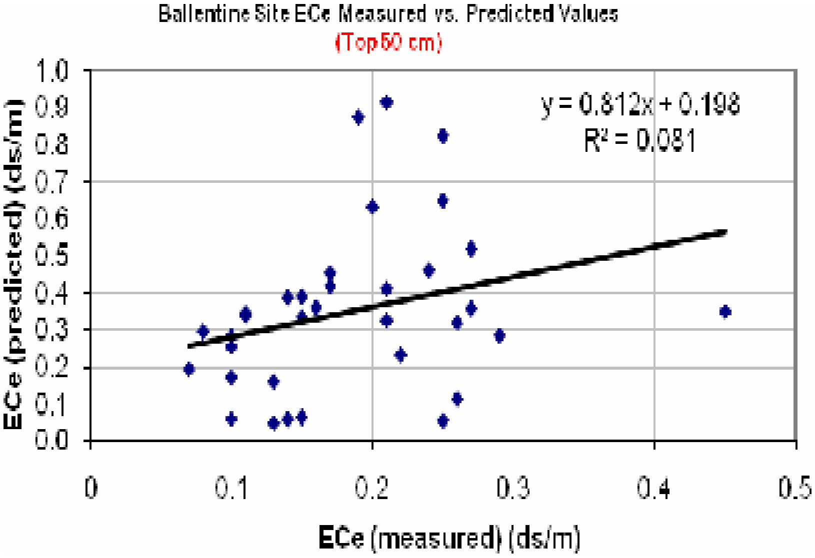

Fig. 18. Correlation analyses results for measured and estimated EC_e values for depths ≤51 cm

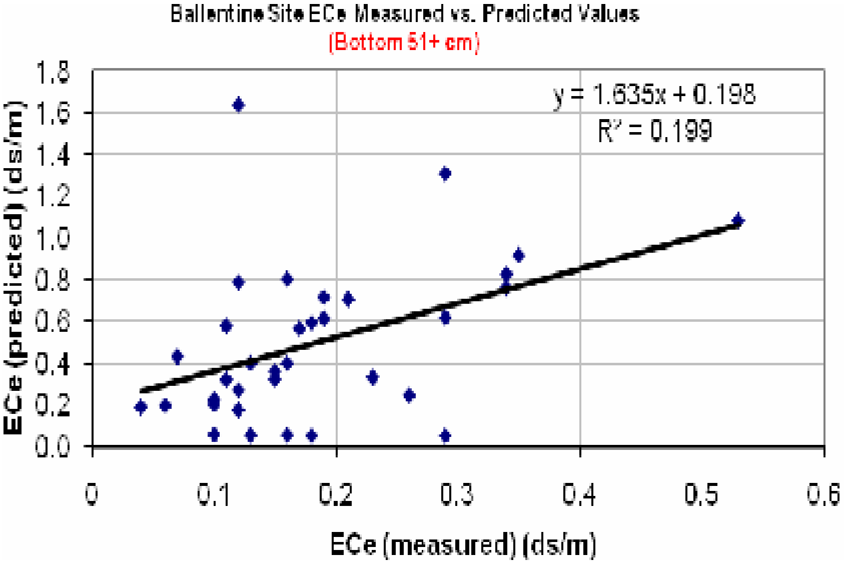

Fig. 19. Correlation analyses results for measured and estimated EC_e values for depths > 51cm

The correlation analyses results showed that correlations were poor for both top and bottom portions of the soil with R^2 values of 0.081 and 0.199, respectively. No clear relationship was observed between the measured and estimated EC_e values. In the last step of the analysis, the correlation analyses were conducted for the estimated EC_e values after the initial estimates were corrected for the actual temperature of the soil at the time of the measurements, which was 23.89 C. The results of the correlation analyses are shown in Figure 20 and Figure 21.

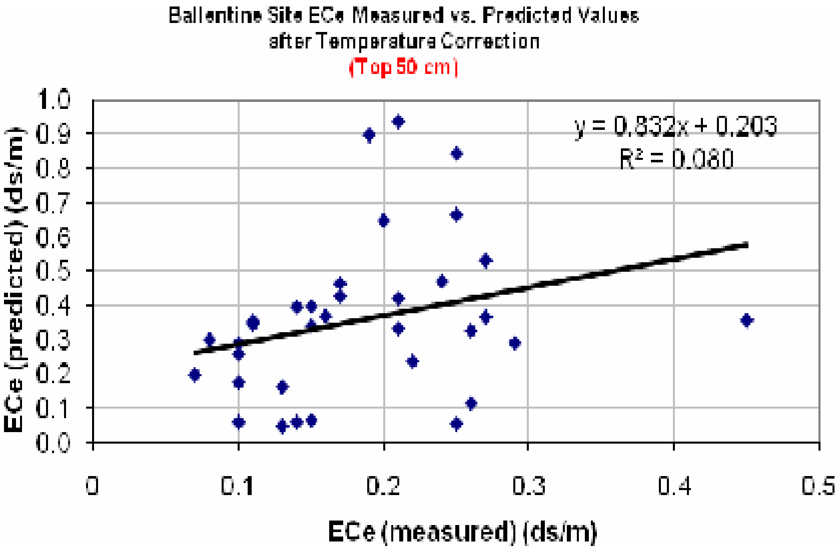

Fig. 20. Correlation analyses results for depths ≤51 cm after temperature correction

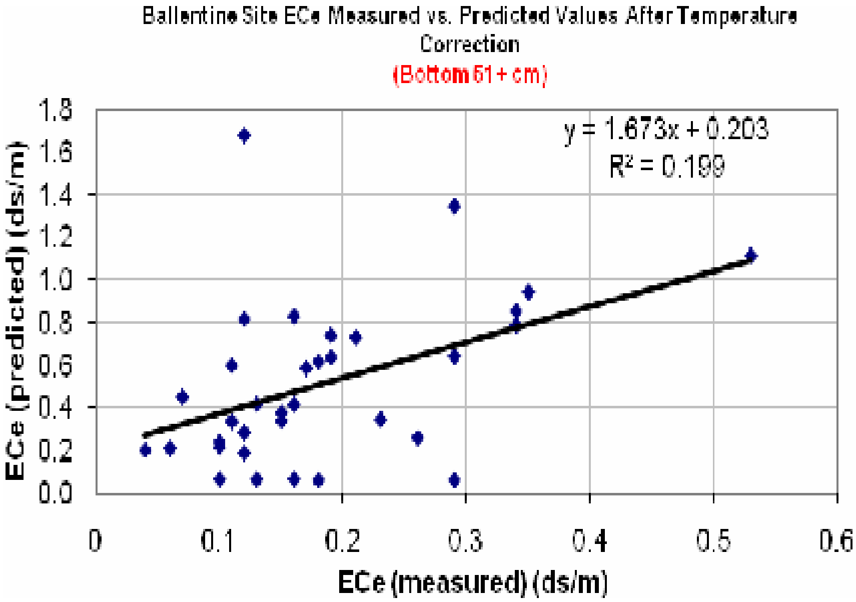

Fig. 21. Correlation analyses results for depths > 51cm after temperature correction

The correlation analyses showed again poor relationships between the measured and estimated EC_e values after the temperature corrections were made with R^2 coefficients of 0.080 and 0.199 for the top and bottom portions of the soil core. In fact, it was observed that the temperature correction did not have any significant impact on the results and the results before and after the temperature correction were very similar.

The correlation analyses showed that use of resistivity values obtained with SIS diver measurements to estimate soil salinity requires more research and possibly employment of additional relationships before the resistivity values can be used to estimate the soil salinity. Unlike electrical conductivity measurements, which are stationary measurements taken with a set up fixed at a certain point in the soil, SIS diver measurements are dynamic and provide continuous measurements over a depth of soil. Because the resistivity measurements obtained in constructing Equations 5 through 10 and those resistivity values measured with the SIS are based on different methods, it appears that there is no one to one correspondence between them. For example, the resistivity measurements reported in the literature are taken over a large volume of soil, while the SIS measurements are valid within some 30 centimeters distance from the sensor. The impact of this difference on the estimation process is currently unclear. However, due to the limited budget of the project, which was 50 hours, no further investigation was carried out to improve the results.

One way of improving the estimates would be an in depth analysis to find a way to translate the dynamic resistivity measurements obtained as the SIS probe moves in the soil through the sensors to the measurements obtained with a static set up at the surface to measure the electrical resistivity. In order to achieve this, a more detailed research is recommended to understand the measurement methods used in the literature with a focus on the impact of the measurement depth and scale on the electrical conductance.

CHAPTER VI

EVALUATION OF FULFILLMENT OF INTERNSHIP OBJECTIVES

In accordance with the Doctor of Engineering program manual, the objectives of the internship should be demonstration of “an ability to apply knowledge and technical training by making an identifiable engineering contribution in an area of practical concern to the organization or industry in which the internship is served” (Texas A&M University, 1999). The internship is also expected to “enable the student to function in a nonacademic environment in a position where the student becomes familiar with the organizational approach to problems in addition to traditional engineering design or analysis. These may include, but are not limited to, problems of management, environmental projection, labor relations, public relations and economics”.

I fulfilled the first internship objective by applying a diverse knowledge and technical training obtained during the program coursework in three commercial research and development projects that required distinctly different approaches and solution methods. Because the internship company’s business environment was highly competitive and uncertain, this required me to adopt to changing client and problem solution requirements through my internship projects. The competencies I gained during my Doctor of Engineering coursework allowed me to cope with these challenges and continue to assist me to do so in my current professional life.

Because the internship company is a small business and a project based organization, I utilized the basic principles of CVEN 668, Advanced EPC Project Development when prioritizing the project objectives, determining project durations and budgets, and monitoring progress, schedule and budget. Meeting the project objectives within the budget played a crucial role in all the projects for the company's profitability. This in turn required an effective implementation of the project planning and management skills. However, one challenge that I faced was the difficulty of applying formal project planning and management methods to my internship projects, which were research and development projects. In my experience, research and development projects in the industry go through little or no preparation process as the contractor company undertakes to deliver a solution for a well defined problem. Often times the budget is fixed before the solution requirements are known to all parties clearly. The principle researcher would be then responsible for employing the right methods, tools and required activities that may or may not be known *a priori* to reach that objective were relatively uncertain and determined in the course of the project. This unfolding nature of research and development projects make it difficult to set a detailed baseline plan consisting well defined activities determined from past experience in previous projects and follow the project progress in accordance with that baseline.

I used the knowledge I gained in MGMT 680, Business and Corporate Strategy, extensively while conducting the strategic industry environment analysis as part of the drainage project. I also used the knowledge I gained in CVEN 603, Environmental Management, when addressing the environmental impacts of subsurface drainage systems due to the nitrate releases from these systems into surface water bodies. However, although my background in environmental law, which I gained in this course, helped me to understand the interactions between drainage design, stakeholders involved and the environmental impacts of drainage systems, the focus of my efforts was mostly on the effectiveness of drainage systems from the perspectives of farm owners and drainage contractors.

The quantitative skills I gained during my Doctor of Engineering coursework played a crucial role in solving the center pivot optimization problem. I used the mathematical and optimization problem solving skills extensively, which I gained in STAT 601, Statistical Analysis, MATH 601, Higher Mathematics for Engineers and Physicists, and INEN 628, Non-linear and Dynamic Programming.

In addition to meeting the technical objectives of the internship and the internship projects, the internship also provided me with an opportunity to understand the tight coupling between engineering research and development principles and business goals, which helped me to achieve the second major objective of this internship. I had a chance to understand the financial, organizational, project constraints of a research and development project and operate within them. One of the important observations I made was that even in highly technical research and development efforts, the value of the effort is often measured in short term returns (e.g. payback) and the business need drives the solution. Therefore, understanding the business plays a crucial role in project success, even in highly technical research and development projects.

Finally, it is my opinion that the Doctor of Engineering program provides an opportunity to reduce the gap between theory and practice, which is often observed in many industries. Because the Doctor of Engineering program provides a diverse and extensive coursework, a Doctor of Engineering program graduate working in the industry is more likely to identify such gaps between the theory and practice and apply some of the knowledge he or she obtained during the program coursework into a practitioner problem. For example, in my current job as a practitioner, I had a chance to successfully apply a strategic assessment tool proposed by a research paper that I used during my Doctor of Engineering coursework (CVEN 641) at Texas A&M University to one of my projects to assess the organizational alignment between the contractor and the owner, which in turn provided valuable insights about the internal organizational environment of the project. I believe the Doctor of Engineering candidates and graduates should continuously try to identify the gaps between theory and practice and apply innovative solutions developed in the literature to practice in order to improve the contributions of engineers to the society.

CHAPTER VII

CONCLUSIONS

Throughout my internship, I have observed that a major difference between an academic and industrial research and development project is the pressure due to the competitive environment of the industry. The highly competitive environments in many industries pose unique challenges for research and development projects in the private sector. For example, competitive pressures such as the threat of new entrants in the business area may limit cooperation and knowledge sharing with outside entities. Small businesses are particularly vulnerable for the competitive pressures. The SIS, which is patented by STI, serves as a barrier for new entrants in this industry due to the development costs and the uncertainties as to whether an effort to create a similar system can be successful. This strategic advantage of STI compels STI to limit cooperation and knowledge sharing with outside entities at times in order to prevent a potential competitor to duplicate STI's systems and services without the costs incurred by STI. However, at times this also hinders transfer of outside expertise and input into STI, which can potentially improve its systems and services and, in turn, increase the company's profitability.

In my opinion, another disadvantage of conducting development projects in small businesses is the limited resources. Bringing a potentially valuable idea or initial results that can potentially turn into an end product or service that can add value requires resources at all phases of the development process. Because small businesses face substantial risks of financial losses in the case a costly development project fails, they have to take the risks carefully when choosing inhouse research and development projects. A potentially risky project with an uncertain outcome but a potentially much higher return and value may be acceptable for a large business. However, a small business may be forced to select only much safer projects when allocating limited resources, even if these projects promise a lower return and value. Because such an idea is also a potential barrier of entry for the company's competitors if it succeeds, finding outside entities who can commit resources to further develop such an idea is relatively difficult as it is likely that such a commitment would require the small businesses to share the specifics of the idea with such entities. Small Business Innovative Research (SBIR) programs funded by the government agencies (e.g. USDA, DOE, DOD) provide valuable resources for small businesses to overcome this disadvantage.

Similarly, unlike in the academia where research results can be shared with an audience who has expertise in the area of interest, in commercial research and development projects end users often have limited expertise or technical background, which pose challenges in communicating the research results and putting the research into practice. An example for this gap between the theory and practice is the limited application of the drainage theory developed to date in the area of drainage design and installation. Although considerable achievements have been made in drainage design and versatile methods and models are available in the literature, only a fraction of them are put into practice by the practitioners and a majority of practitioners continue to design and install subsurface drainage systems solely based on experience. In my opinion, this gap can be overcome by large corporations who can identify the cost savings and other benefits of potential improvements at large scales and commit the necessary resources for long term benefits. Enterpreunal farm owners and contractors can also serve as an example by adopting improved methods if such methods increase competitive pressure on other farm owners and contractors.

One major observation I made during my internship is that in small, knowledge based companies (i.e. small consulting firms), where the business environment requires the company to respond to the changing needs of the industry in which the company serves, professionals of the company should have diverse backgrounds in order to respond to the changing requirements and skill sets that may vary from project to project. Because small knowledge based businesses should operate in a cost effective way with minimum overheads and slack resources in order to be able to compete with larger companies in the same industry segment and remain flexible at the same time in order to respond to the clients' changing needs, this requires that professionals of such a small business should have a diverse background that would enable them to respond to these requirements. I believe the diverse background I gained during my Doctor of Engineering prepared me well to meet these challenges. For example, the need for the application of various technical skills, such as mathematical modeling, project management and strategic strengths, weaknesses, opportunities and threats (SWOT) analysis, which I gained from various courses that I took during my Doctor of Engineering coursework, to the changing requirements of the projects that I was assigned to helped me to integrate these skills in order to complete these project successfully.

Internship Supervisor and Duration

The internship supervisor was Nick Guries, who is a Civil Engineer with STI. The internship was completed in 13.5 consecutive months starting on October 3rd, 2005.

Confidentiality

STI has recently negotiated a one year contract with Deere and Company and the research and development projects described in this proposal are subject to this contract. The intern is obliged to conform to the confidentiality conditions stipulated by the contract signed between STI and Deere and Company, as all deliverables of the internship will be the proprietary knowledge of STI and Deere and Company. However, using this report does not violate these confidentiality conditions and the intern has permission to use the information in this report to meet the Doctor of Engineering degree requirements.

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VITA

Bilge Kagan Ceylan received his Bachelor of Science degree in Civil Engineering from The Middle East Technical University at Ankara, Turkey in 1992. He entered the Civil Engineering program at Texas A&M University in August 1992 and received his Master of Science degree in December 2004 in the field of water resources and environmental engineering. He started his doctoral studies at Texas A&M University in January 1999 and received his Doctor of Engineering degree in May 2008. His research interests include infiltration and spreading of lighter than water non-aqueous phase (LNAPL) liquids in porous media, flexible construction project delivery systems and application of real options theory in construction project planning. Bilge Kagan Ceylan published two peer reviewed papers on these topics in the journals of Water Resources Research and Defense Acquisition Quarterly. Mr. Ceylan has more than 8 years of professional experience in the construction industry.

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