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DELINEATION OF MANAGEMENT UNITS FOR SITE-SPECIFIC IRRIGATION

A Dissertation
Presented for the
Doctor of Philosophy Degree
The University of Tennessee, Knoxville

Carlos Wagner Oliveira

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DEDICATION

This dissertation is dedicated to my parents, Luis Carlos Oliveira and Francisca Maria Souza Oliveira, great role models and friends, and to my siblings, Carla, Danuzia, Deisa, Carmen and Luis Oliveira, and the rest of the family, for always believing in me, inspiring me, and encouraging me to reach higher in order to achieve my goals.

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ABSTRACT

Variability of soil properties in many fields is too great for a whole field to be effectively managed with a uniform application of irrigation water. Consequently, a decision must be made for irrigation management about which areas in the field should be treated differently or grouped. A decision-making framework was developed to determine whether site-specific irrigation management would be cost effective for selected fields. The framework is designed to find the best field layout in terms of water management, and tests the hypothesis that there is a particular field management layout that maximizes net return. As part of the framework, a merging algorithm recursively combines adjacent sub-areas with differing soil units until the whole field is merged into one management unit. The decision-making procedure creates different field layouts; the selection of the best layout is then based on an economic analysis. There is a trade off between increased yield and gross returns with the increased costs associated with the site-specific irrigation. There may exist a layout somewhere between the maximum number of divisions (completely site-specific irrigation) and complete grouping (uniform irrigation) that maximizes profit.

The general framework was applied to a field in Cocke County, Tennessee that had been intensively soil mapped. Five different soil types in the field made up six different potential soil-management units. From the soil mapping information, six different management layouts were created. A site-specific irrigation schedule based on 31 years of climate data and a yield response equation were used in the analysis. A yield estimation function was used with the assumption of maximum yield; water stress was the only yield-reducing factor that was considered. Average tomato prices for the years of

the analysis were corrected for the price base of 2001, the last year of the analysis. The water applied in each layout was dependent on the year of analysis. The average water applied was not significantly different for the layouts ($P>0.73$). However, the expected average tomato production was dependent on the layout, and was significantly different for site-specific irrigation as compared to uniform irrigation of the entire field ($P<0.0001$). The decision-making framework with the merging algorithm identified the layout (layout 4, net annual average return = $282,282) that maximized profit, as compared to uniform irrigation (layout 6, net annual average return = $238,433). In the completely site-specific management layout (layout 1), the yield increase compared to layout 4 was negligible, and the increased costs to treat each management unit individually decreased the return (net annual average return = $281,352).

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NOMENCLATURE

cwt	hundredweight
h	hour
kg	kilograms
l	liters
m	meter
min	minutes
mm	millimeters
t	metric ton
A	acre
ha	hectare
$	dollar
lb	pounds
s	seconds
bu	bushel
gpm	gallons per minute
W	watts
kW	kilowatts
hp	horsepower
gal	gallons

Abbreviations

ChA	Chewacla soil series
CoA	Congaree soil series
StA	State soil series
BuA	Buncombe soil series
ToA	Toccoa soil series
MU	management unit
MUs	management units
MMU	minimum management unit
MMUs	minimum management units
GIS	geographic information system
VRT	variable rate technology
GPS	global position
DGPS	differential global position system
EMI	electromagnetic induction
AWHC	available water holding capacity
TAM	total available moisture
RAM	readily available moisture
MAD	manageable available water
SMD	soil moisture depletion
ET	evapotranspiration
NR	net returns
N	North
W	West

ET_a	actual evapotranspiration
ET_o	reference evapotranspiration
ET_m	maximum evapotranspiration demand
I	net irrigation amount
P	effective precipitation, mm;
d	time index, day
i	space index (sub area within a field)
R_d	effective root depth
CC	cost of crop
HL	harvest cost
SL	set-up labor cost
CH	headline cost
VFL	fuel and lubricant cost
CCU	cost of control unit
TC	total costs
SSIS	site-specific irrigation schedule
P	probability level of significance of the statistical test

CHAPTER 1

INTRODUCTION

Problem statement

One of the main problems related to irrigation management is the spatial variability of the soil chemical and physical characteristics within fields. This variability is often too great for a whole field to be effectively managed with a uniform application of irrigation water. However, for irrigation management decisions, fields are typically assumed to be homogenous because cost limitations and constraints of irrigation system layout limit management to treating a field as a whole. Most of the soil properties used to determine irrigation demand are known, but it has not been practical to measure the properties at spatial scales with sufficient resolution for site-specific irrigation management. Topography changes, soil differences, and drainage conditions determine some of the requirements necessary for optimizing the use of inputs such as water for specific areas of each field. When water is applied in the field, many of the irrigation management models that are used to determine irrigation amounts will lead to inefficient use of water and chemical inputs associated with production, because an average application depth is used. As Burrough and Swindell (1997) stated, the driving force behind wanting to understand soil variability is a need for improving control over the physical environment so that returns are maximized for each management unit.

Precision farming has partially addressed spatial variability by providing tailored management decisions based on the site-specific soil properties. The problem of irrigation management related to soil variability was partially solved by the creation of

site-specific irrigation systems (Sadler *et al.*, 2000a). These site-specific systems apply custom quantities of water to sub-areas in the field that are pre-defined by the operator.

One of the assumptions in all site-specific irrigation designs is that the soil spatial variability has been identified and grouped or classified in some orderly way to reach a desired goal. Classification or grouping implies differentiated irrigation requirements. This is the difficulty in designing site-specific irrigation systems. When classifying or grouping, which areas in the field should be treated differently or should be grouped? What criteria should be used to decide if a field should be treated as a whole, or if certain areas should be treated separately?

The answer, to some extent, depends on the purpose of the irrigation set-up. For example, research plots in a field may require different irrigation treatments, but for commercial fields the most important criterion is usually economic return. When considering completely individualized treatments (site-specific irrigation) increasing the yield to obtaining a high gross return, may also increase costs and reduce profits. In the same way, in grouping management units may reduce costs to increase profits, but only to the point at which the yield is reduced due to the large variability within each group, thereby decreasing profit. There is therefore a trade off between the two extremes of management unit layouts, which suggests that there may exist a layout between the maximum number of divisions (completely site-specific irrigation) and complete grouping (uniform irrigation) that maximizes profit.

Sometimes the task of identifying irrigation management units is given to technicians or farmers. For example, the Variable Rate System developed by the University of Georgia (Perry *et al.*, 2002; Perry *et al.*, 2003) was based on an irrigation

management map developed by the farmer. The map was based on aerial photographs, yield maps, soil survey maps, and the farmer's knowledge of the area. With this approach, it is not clear what procedure was used to divide a field into different management zones in order to optimize irrigation applications. Water application or irrigation management is sometimes limited by the irrigation design (hardware implementation), which may or may not comply with the field spatial variability.

For applying site-specific irrigation some pertinent questions must be answered:

1) What soil properties are important (or relevant) in zoning a field for different treatment areas (management units - MU) for irrigation?
2) How many management units should be delineated in the field?
3) More importantly, what production and economic criteria justify different areas in the field having different irrigation management control?

There is clearly a lack of a framework to address these questions. There is also pressure from society to conserve water. Site-specific systems have the potential to conserve water, by avoiding over-irrigation. The excess water can cause yield reduction and/or leaching of nutrients that can cause environmental problems. This makes the identification of management units a timely issue to be addressed.

A site-specific irrigation system obviously includes an extra cost of production that has to be balanced with the benefits it can provide. Additionally, farmers are faced with economic consequences of production decisions relative to scale and the costs inputs and equipment. Therefore a decision-based framework is required to delineate and

evaluate management units for site-specific irrigation, and to answer some of the questions stated above.

Research objectives

The primary goal of this research was to develop a conceptual framework to answer the basic question:

Should a field be treated as a whole (uniform irrigation application), or should sub areas in the field be treated individually (site-specific irrigation application) for irrigation management control?

More specifically, the objectives of this study were:

1. Decide how management units should be delineated in a field, based on soil properties that are relevant to irrigation management.
2. Develop and implement a procedure to decide the size, number, and layout of the different management units (sub areas) based on the economic response of each unit to irrigation water applied under a certain layout.
3. Provide a general framework that addresses the topics above and can be used for different combinations of weather, soil, and crop.

CHAPTER 2

LITERATURE REVIEW

Soil spatial variability

Soil variability observed in the field is caused by the interaction of the factors that influence soil formation. Five factors that can be enumerated as influential in soil formation are parent material, climate, living organisms, relief, and time. For the most part, soils are the same wherever all elements of the five factors are the same. Soil in this study is defined as a natural body comprising solids, liquid, and gases that occurs on the land surface, occupies space, is characterized by a number of properties, and has the ability to support rooted plants in a natural environment (NRCS, 2002).

One way to identify soil variability is to classify the soil. The objective in any classification is that the variability within any class is, or is hoped to be, less than that in the whole population and is small enough for a generalization or a prediction to be useful. With this objective in mind, the Natural Resource Conservation Service (NRCS) establishes procedures for soil survey where soils are identified based on a system of classification and taxonomy. The current system of classification defines classes in terms of observable or measurable properties of soils, and has six categories. Beginning with the most inclusive, these categories are: the order, the suborder, the great group, the subgroup, the family, and the series. Other subdivisions within the series are soil type and phases. Taxonomy refers to definitions and nomenclature used to classify soil. A more complete definition of the terms is given in the National Soil Survey Handbook (NRCS, 2002).

The basic objective of soil surveys is to gather information about soil occurrences, location, and distribution. This is the same for all types of land, although the number of mapping units, mapping unit composition, and the detail of mapping vary with the complexity of the soil patterns and the specific needs of the users. Most soil surveys in the U.S. are designated second order (Order 2) and have scales from 1:12,000 to 1:31,680, with minimum size delineation of 0.6 to 4 ha (1.5–10 A). Order 2 surveys were developed for intensive agriculture, which requires detailed soil information for general planning purposes. A first order (Order 1) soil survey uses scales larger than 1:15,840, with minimum size delineation of <1 ha (2.5 A). Order 1 surveys are needed for applications requiring very detailed soil information (Soil Survey Division Staff, 1993). For example, the Tennessee Soil survey series provides soil-mapping distribution at a scale of 1:20,000 (Order 2).

In both Order 1 and Order 2 surveys, the main mapping unit is designated a consociation. Order 2 surveys generally contain more complexities and associations than Order 1. A consociation by definition is dominated by a single soil (the soil in a consociation may be identified at any taxonomic level), with at least 50% of the area within the consociation boundary consisting of the dominant soil taxon; less than 15% of the area consists of dissimilar soil series, or <25% if the soil series has similar properties. Complexes are soil groupings that cannot be mapped separately at 1:24,000, while associations are groupings that can be mapped separately at 1:24,000 scale. However, the actual practice of delineation regarding how these entities are eventually mapped has some flexibility, so that the survey crew or state survey team has considerable freedom in interpreting the definitions of similar and dissimilar (Soil Survey Division Staff, 1993).

To improve the resolution of mapping, soil scientists and engineers at The University of Tennessee used differential GPS units and ground truthing by soil survey personnel to produce detailed soil maps (Gehl, 1999; McDaniel, 2001). The smallest sampling unit varied from 0.1 to 0.4 ha (one per quarter acre to one per acre). The intensity of the soil sampling was approximately equal to the 1:7,920 scale traditionally used in the United States for individual soil mapping for conservation planning. At this scale, areas of 0.2 to 0.4 ha (0.5 to 1 A) can be easily delineated. In contrast, at a typical soil survey scale of 1:24,000, soil areas have to be approximately one order of magnitude larger, i.e., 2 to 4 ha (5 to 10 A), to be conveniently delineated. Comparison of these 1:7,920 maps with the 1:20,000 of the Soil survey by county shows a general resemblance for some fields, while for other fields there is no resemblance at all (Gehl, 1999; McDaniel, 2001).

With the objective being to better understand soil variability, the use of quantitative methods such as geostatistics and state-space approaches has been introduced into the realm of soil characterization (McBratney and Pringle, 1997; Lark and Bolam, 1997). The application of geostatistics, particularly kriging and cokriging (Vauclin *et al.*, 1983; Jaynes, 1996; Mahdian and Gallichand, 1997), and scaling theory (Simmons *et al.*, 1979; Russo and Bresler, 1980; Western and Bloschl, 1999) are steps that have been made toward the characterization of fields on the basis of the variability of observations from those fields. Early studies to quantify the variability in particular fields (Nielsen *et al.*, 1973; Greminger *et al.*, 1985; Saddiq *et al.*, 1985; Goovaerts and Chiang, 1993) of soil water content or soil-water characteristics, found that the variability was spatially dependent and was a function of the method of water application, time since the last

water application, and the magnitude of the soil water tension (which is related to soil texture variation).

Currently, the majority of available technologies and applications in site-specific farming utilize the map-based method of pre-sampling, map generation and variable-rate application. This method is most popular because of the lack of sufficient sensors for monitoring the soil conditions. Additionally, laboratory analysis is still the most trusted and reliable method for determining most soil properties (McBratney and Pringle, 1997). However, the cost of soil testing limits the number of samples that a farmer can afford to test. Thus, grid soil sampling methodologies have been studied to provide information on soil variability at a lower cost (Pocknee *et al.*, 1996). Strategies to design sampling techniques were investigated by Brus and Gruijter (1997). McCann *et al.* (1996) were able to delineate management units (MU) for site-specific farming on large fields (32 to 64 A) operating at low input for dry land operations. They used aerial photographs (1:30,000 scale) associated with existing soil survey information (1:100,000 scale) and ground truth data to identify the management unit at a low cost.

Upchurch and Edmonds (1991) gave an overview of some of the statistical procedures that were used to quantify and describe the spatial and temporal variability within mapping units. They briefly described parametric and non-parametric statistics, which require a prior knowledge of the probability distribution of the population. Methods based on the theory of regionalized variables were also described. According to the authors, the regionalized variables methods are an extension of classical statistical tools with the assumption of dependency of the samples.

Chung *et al.* (1995) studied the effects of farming activities on sampling strategies. They concluded that farming activities could profoundly affect spatial variability of soil properties, in particular for K and P. The results suggested that a transect of soil samples should be collected in the direction perpendicular to the direction of farming operations. However, some soil properties such as bulk density were less affected by farming activities. Other studies (Goovaerts and Chiang, 1993; Lascano *et al.*, 1999; Van Pelt and Wierenga, 2001) have shown that even with this temporal and spatial variability of soil water content there is a constant pattern to the spatial variability that does not change with time. This phenomenon is described as temporal stability.

Precision farming

To address the problem of spatial and temporal variability, the concept of precision farming was introduced. Precision farming, precision agriculture, and site-specific crop management (SSCM) are terms used to describe technologies that modify current techniques and incorporate new ones into the production process. These approaches consider sources of variability such as non-uniformity of the soil and yield variability within a field and modify the production conditions to improve the outcomes. Blackmore (1994) described these technologies as not simply the application of treatments at the local level, but requiring a sufficient understanding of the processes involved in applying the inputs in such a way as to achieve a particular goal. Often these goals are increased production efficiency and reduced risk of adverse environmental impact.

Aspects of precision farming

The technologies that made precision farming possible include computers and microcomputers, global positioning systems (GPS), sensors (including yield monitors), geographic information systems (GIS), and variable rate technology (VRT) controllers.

A wide range of new applications has developed with the incorporation of computers in agricultural production. Computers work as the central system for storage, analysis, and making decisions. They are also often embedded within other technologies to provide control. Software packages that are useful in site-specific applications are the ones able to make prescriptions based on measured parameters, forecasting, or data based decisions.

One of the major components of precision agriculture is GPS, which provides the exact position in a field for site-specific monitoring or application. The GPS was developed by the U.S. Department of Defense. A constellation of 24 NavStar satellites was completed in 1994, and a minimum of 3 satellites is needed to calculate a field position. The U.S. National Geodetic Survey (Milbert, 2000) reported that position accuracy has improved such that 95% of the points fall within a radius of 4.1 m.

Sensors that collect soil and/or weather parameters are often used in precision farming. The most common site-specific sensors are the ones that measure harvest yield. Some sensor systems simply track the yield monitor display during harvesting, while others couple the monitor output with position information from combine-mounted global positioning systems (GPS) to create yield maps for post-harvest analysis. According to Blackmore (1994), Massey Ferguson was the first company to produce a commercial yield-mapping combine. The output from the combine was a data file that recorded the

position of the combine, in latitude and longitude, and the yield at that point. A number of other similar sensors have been developed for site-specific use.

A GIS is a computer software package that can be used to manage, analyze, and display geo-referenced, multi-attribute data (Lu *et al.,* 1997). The GIS supports yield mapping, and other maps such as soil type and texture, organic matter, soil moisture, topography, and soil fertility. With information organized in layers, a cross-layer analysis can help farmers determine recommendation plans. Zhang *et al.* (1999) developed GIS software that was directed to precision farming research. It included some basic and advanced analytical tools that are necessary for research in precision farming. Originally, the first function of the field GIS was to store and manage the spatial database. More specifically, the required functions for site-specific farming information system were identified as: 1) functions for integrating spatial data from different sources with different scales and resolutions; 2) functions for insulating, partitioning, or blocking spatial regions to simplify analysis with a multi-factorial environment; 3) functions for spatial pattern analysis in both Cartesian (square grids) and polar (center-pivot field) coordinate systems; and 4) functions integrating remotely sensed data into the analysis.

Data stratification

In precision farming, the variation of field properties and the required production inputs to match the soil variability are often known. However, the continued use of VRT is unnecessary once small regions with uniform soil properties within the field are identified. On small areas the application rates can be constant. The ultimate objective is

to divide the field into areas that are relatively homogeneous, and that relate the dynamic and static soil properties to expected yield.

Traditionally, there are at least three methods to stratify sites into units with similar productive potential: 1) detailed soil surveys, 2) extensive sampling programs, and 3) sensor based survey technologies.

Soil survey

For the first approach, Jessip *et al.* (1999) used spatial geo-referenced elevation data and soil survey maps with infiltration information as the resource to delineate hydrologic management zones. Sadler *et al.* (2000b) evaluated the variation in several physiological and physical characteristics of the crop, both in space and across soil map units. Measurements included plant population, height, leaf area index, and aboveground biomass and yield components. The objective was to compare paired samples of four soil map units (mapped at 1:1200 scale) to determine if grain yield variation was of practical value to precision farming. It was concluded that to create soil management zones for precision farming, one must use detailed soil map units with additional spatial data, such as yield maps. Franzen *et al.* (2002) found that Order 1 soil survey scales show similarities with Nitrogen-N management zones obtained with grid and topography-based zone sampling. However, Order 2 soil survey scale maps should not be used to develop N management zones for site-specific agriculture unless the soil pattern is verified with other zone development tools for site-specific management.

Sampling and interpolation

A second approach uses sampling along with interpolation techniques to estimate the spatial distribution of soil properties. Han *et al.* (1993) developed a data blocking

procedure to convert conventional soil sampling information, such as a point soil data set, into a new data set in which the data are presented in cells, with values representing each cell. In this same study, a non-parametric distance-weighting algorithm was used to interpolate the data for points that were not surveyed originally. The non-parametric algorithm produced about the same estimation errors as kriging, but it worked much faster.

Sensor based survey

The third approach use sensors to survey the desired properties directly or indirectly. Sudduth *et al.* (2001) used an Electromagnetic Induction (EMI) sensor adapted to a mobile vehicle to estimate topsoil depth on claypan soils. Jaynes (1996) pointed out that there are at least three ways in which Electromagnetic induction (EMI) surveys can be used in field mapping: 1) A EMI survey can be used as a reconnaissance map to aid subsequent soil sampling; 2) EMI data can be used as co-regional data to refine maps of sparsely-sampled soil properties using cokriging; and 3) EMI data can be used as direct surrogate measurements of a second soil property. For example, this approach was used to map atrazine sorption affinities using EMI surveys. The electrical conductivity of a soil is affected by a combination of several factors. Once these factors have been established through measurements and calibration, a correlation between the electrical conductivity and particular soil property can be obtained. The soil electrical conductivity is affect by a combination of soil water content, dissolved salt content, clay content and mineralogy, and soil temperature.

In another example of real time sensing of soil properties, Hummel *et al.* (1996) developed two optical soil organic matter sensors. One of the sensors when calibrated

could be used to sense soil moisture (R^2 = 0.94) and cation exchange capacity (CEC). Depth to clay was also estimated based on EMI measurements, which were regressed (R^2 = 0.81) with soil probe measurements. Akbar *et al.* (2001) examined two salinity models for real time soil moisture estimation and one-time calibration of electromagnetic induction sensors using apparent soil electrical conductivity. Kaleita and Tian (2002) studied the relationship between soil moisture, soil organic matter content, and remotely sensed spectral measurements. They used both ground based spectral reflectance in visible and near-infrared wavelengths. The surface soil moisture was collected in an automated way with a Theta probe (Dynamax Inc.) The voltage readings were converted to volumetric water content based upon calibration coefficients. Principal component analysis and regression techniques, among other approaches, were used to established the relation between spectral reflection data and soil moisture (R^2 = 0.62). Adamchuk *et al.* (1999) created an automated soil sampling system for measuring soil pH on the go. A simple linear regression was used to calibrate the mV output of the electrode against soil pH obtained via a standard laboratory method. The sampling system was able to collect soil pH readings at a selected depth (0-20 cm) every 8 s (R^2 = 0.83).

New methods

Other technologies such as fuzzy logic have also been incorporated into the soil classification process. Kollias and Kalivas (1998) enhanced a GIS with fuzzy capabilities to classify an area according to degradation from agricultural uses and to suitability for growing alfalfa. According to the authors the fuzzy processing capabilities can enhance a GIS in three ways: 1) it can easily manipulate the natural variation of soil properties; 2) it allows the users to express subjective views on the stored data in the form of membership

grades; and 3) it presents a more precise and realistic classification and assessment of land resources. There is considerable literature (Burrough *et al.,* 1992; Odeh *et al.,* 1992a, b; McBratney and de Gruijter, 1992; Dobermann and Oberthür, 1997) about the use of fuzzy theory and fuzzy clustering techniques to implement soil classification.

Relating yield to precision farming

In spite of these successes, these methods are solutions to only part of the problem. They can provide a way to physically stratify information and delineate the management units based on the level of information available. However, there is still need for evaluation of the management units obtained from a technical and economic point of view. To evaluate or optimize the management units created by these methods, researchers have usually made use of independent data. The most commonly used variable is yield. The objective is to create management units to reduce the variability in yield so that the maximum economic yield can be obtained. One problem with this approach is that yield variability may be caused by factors other than the ones used in the analysis. Indeed, yield is a very complex variable affected by a combination of spatial and temporal factors (soil, weather, and management) that go beyond soil variability. Several researchers have tried to establish the relationship between inputs and yield variability.

At first, more emphasis was given to variation in soil fertility than to other parameters, which were eventually included in the analysis (Cambardella *et al.*, 1996; Khakural *et al.,* 1996; Mallarino *et al.,* 1996; Sudduth *et al.,* 1996; Sudduth *et al.,* 1997). After many attempts, it was observed that there has been little success in correlating yield to spatial patterns in fertility (Pierce and Nowak, 1999). On the other hand, the

dependence of yield on applied water is known, especially in arid areas where water is the limiting factor. There is a nearly linear dependence of yield on applied water that has given rise to the water use efficiency concept and crop production functions (Howell *et al.*, 1990). This knowledge, associated with the fact that water availability to the plants is dependent on water holding capacity of the soil, which itself is related to soil texture that varies spatially, gives an indication of the potential of water variability to explain yield variability. In fact, Paz *et al.* (1998) was able to explain 69% of the yield variability of soybeans by considering water stress alone.

In a multi-disciplinary study conducted by a team from USDA-ARS and Colorado State University (Heermann and Buchleiter, 2002) evaluated the impacts of precision agriculture on crop production; hydraulic conductivity, texture, and elevation were identified as major factors that contributed to spatial yield variability. The research confirmed that changes in the management of the irrigation system could potentially reduce the variability in yield due to differences in the soil water parameter. Nevertheless, there is a lack of a framework for site-specific water management implementation. Bouma (1997) stated that a major challenge for science is to present methods that characterize variability in space and time in a manner in which farmers can use the information to improve their management decisions. As Burrough and Swindell (1997) stated, the driving force behind wanting to understand soil variability is a need for improving control over the physical environment so that gross returns are maximized for each management area.

Site-specific irrigation

Different water management strategies are required across a field because of differences in soil characteristics and resulting variations in water availability. For example, currently one may chose to: 1) manage the whole field based on average soil water conditions; 2) ensure that areas with the smallest available water holding capacity receive adequate water; or 3) limit water application to avoid over-irrigating the wettest areas. All of these cases will cause over-irrigation or under-irrigation of areas within the field due to non-uniformity of available water holding capacity. Colaizzi (1999) proposed a systematic decision-making framework composed of four layers that can lead to irrigation management in site-specific crop management. The layers are: 1) a pressurized irrigation system that will allow precise delivery of water; 2) automated control, monitoring, and recording of the delivery system; 3) real-time feedback of soil, crop, and meteorological conditions; and 4) models to predict future crop water needs for irrigation scheduling to enhance information resolution on layer 3.

Site-specific irrigation systems

The implementation of these layers has in part been fulfilled, especially the first two components, using existing site-specific irrigation systems (Sadler *et al.*, 2000a; Reeder, 2002). However, the continuous use of variable rate technology (VRT) is unnecessary, because application rates on small areas can be kept constant. As mentioned with other site-specific approaches, one attempt to reduce the variability within a field is to group sections of the field with common characteristics. As a result, each management unit responds more uniformly to the different water depth and frequencies applications.

The reported resolution built into site-specific irrigation systems is about 10, 20, or 30 m, depending on the selected design (Sadler *et al.,* 1998)

Research considering site-specific irrigation has been emphasized at four locations: USDA-ARS Fort Collins, Colorado; University of Idaho; USDA-ARS Florence, South Carolina, and Washington State University. Self-propelled sprinkler irrigation equipment such as linear move and center pivot were modified to provide three approaches for making VRT irrigation sprinkler applications. These include: 1) pulsing sprinklers for time-proportional control (Fraisse *et al.,* 1992; Evans *et al.,* 1996); 2) using multiple manifolds with different-sized nozzles in combinations to create a stepwise range of rates (Camp and Sadler, 1994; King *et al.,* 1995; Wall *et al.,* 1996; Omary *et al.,* 1997); and 3) altering the aperture of a nozzle with an inserted pin to achieve two rates and then cycling the pin for time proportional control between the two rates (King and Kincaid, 1996; King *et al.,* 1997). Buchleiter *et al.* (2000) discussed the advantages and disadvantages of each of these techniques, and the effects of the design on the remainder of the system.

Some automatic irrigation units that have been developed for research can be adapted to perform site-specific irrigation. At the University of Tennessee two of these automatic irrigation controls, have been applied to site-specific irrigation. The first is the "Fuzzy Logic Based Automated Irrigation Control System" developed by Ribeiro (1998), and the second is a "Site-Specific Irrigation Controller" developed by Miranda (2003). The first system relies on a central control developed using the fuzzy logic approach as an alternative to improve the current management technologies. Data from an automated weather station and from soil moisture sensors were used as inputs to the system. The

system operated in a closed loop with soil moisture readings used as feedback information. The second system used an in-field microcontroller to allocate limited water to site-specific zones, based on moisture sensors readings, available water pressure, and a priority level assigned at the zone.

Drawbacks of site-specific systems

The hardware capabilities for site-specific irrigation have been developed and shown to function adequately to apply water on a site-specific basis. This still leaves, however, the problem of prescription and/or design of the area to be irrigated related to layer 4 as defined by Colaizzi (1999), mentioned previously. This last layer follows the "proactive" process described by Bouma (1997), in which predictive modeling is used to anticipate stress within a field. This modeling allows management actions to be taken in order to avoid stress and associated yield reduction. This approach is preferred because highly engineered and expensive irrigation systems require detailed *a priori* knowledge of site and soil conditions. The limiting factor for site-specific irrigation is therefore still the same as it is for other precision farming technologies, which is to identify the variability and make correct control decisions to achieve the desired goal. In site-specific irrigation, the goal may be to avoid crop stress or to optimize economic return, to adapt to treatment variability such as in research plots or nurseries, to allow deficit or partial irrigation to solve limited resource allocation problems, to comply with exclusion zones or other regulatory constraints, to avoid adverse environmental impact, to avoid rock outcrops and roads, or to combine other management tasks with irrigation such as fertilization and/or pest control.

Most often, however, the goal is to avoid crop stress or to optimize economic return. A clear understanding of the interactions of crop, weather, and soil variability is required to establish a management prescription that will achieve the goals of site-specific irrigation.

Plant water relations

Crop growth models

One way to relate the effect of water availability on yield due to spatial and temporal distribution has been through the use of crop growth models linked to soil water balance models that either are embedded in the model or are included as part of the study. Crop growth has long been used to simulate irrigation management impacts on crop yield (Swaney *et al.*, 1983). Mahdian and Gallichand (1997) conducted a study to investigate the regional spatial variability of simulated potato water deficit and yield resulting from irrigation on soils ranging from coarse to medium texture, and using a crop growth model (SUBSTOR). Results from the simulation showed that seasonal regional water deficits were 245, 203, and 153 mm at three exceedance probability levels (10, 20, and 50%). The simulated average yield increase with irrigation was 31.5 and 22% for coarse and medium texture soils respectively. These researchers also evaluated different interpolation methods, with inverse distance weighting providing the best performance (mean absolute error of 35.2%). Beltrão and Asher (1997) implemented a model that modified water content to measure the effects of salinity in a crop growth model (CERES-maize). The model was used to estimate the effects of salinity on corn yield. Several sensitivity scenarios were tested. The results of the simulations were in agreement with field data ($R^2 = 0.75$). Paz *et al.* (2001) used a crop growth model

(CROPGRO-Soybean) to study the effects of water stress, soybean cyst nematodes, and weeds in the yield. These factors often vary spatially in fields and are likely to cause spatially-varied yield. In the best scenario, yield was predicted in good agreement (R^2 = 0.80) with the measurements. Guerra *et al.* (2002) used a crop growth model (EPIC) to estimate crop yield and water demand for corn, cotton, peanut, and soybean in Georgia. The crops were evaluated under rain-fed and irrigated conditions. Under rain-fed conditions, the EPIC model performed fairly well for the different crops, weather, and soil conditions across Georgia. Under irrigated conditions, the model prediction was poor. The model simulated the year-to-year variability in measured irrigation reasonably well only for cotton.

Drawbacks of crop models

Jones and Ritchie (1990) pointed out that some crop growth models allow the user to input specific dates and amounts of irrigation, allowing comparison and selection of the best irrigation strategies. They also claimed that crop growth models are more robust than crop-water production functions for use with different weather conditions. Crop growth information combines irrigation decisions with other management decisions, such as planting date, row spacing, and nitrogen fertilizer use. However, one of the great disadvantages of this approach is the number of parameters that are needed for fitting or calibrating the models (Fraisse *et al.*, 2001; Mavromatis *et al.*, 2001). Procedures have been developed to ease the calibration process (Calmon *et al.*, 1999; Guérif and Duke, 2000; Irmak *et al.*, 2001; Wallach *et al.*, 2001). Nevertheless, the difficulty of parameterization combined with the extra complexity rules out this approach. More

simple or straightforward ways to establish the relationship between water deficit and yield are needed for a practical management tool.

Response functions

In areas where water is a limiting factor, irrigation has a drastic effect on the final yield. The relationship between crop yield and water application has been modeled with functions ranging from linear to curvilinear response (Musick and Dusek, 1980; Pandey *et al.*, 1984; Senthong and Pandey, 1989; Boquet, 1989; Santos, 1998; Holzapfel *et al.*, 2000; Wanjura, *et al.*, 2002; Kipkorir *et al.*, 2002).

Traditional production functions must be adjusted for each soil unit found within a field in order to develop site-specific recommendations. Camp *et al.* (2000) evaluated production functions for specific points within two fields in Florence, South Carolina. Each field had specific soil and terrain attributes. The soils under center pivot 1 (CP1) were fairly uniform. Treatment variables included three irrigation regimes (0, 75%, and 150% of a base rate), four N-fertilizer regimes (50%, 75%, 100%, and 125% of a base rate), and three antecedent crop rotation treatments. Soils under CP2 were more varied and included 12 soil-mapping units. Soil-mapping units were determined by NRCS personnel from samples taken on a 15-m x 15-m grid, with additional sampling to identify soil boundaries. Treatments included 0, 50, 100, and 150% of a base irrigation rate. N-fertilizer rates were those recommended for rain-fed production (135 and 225 kg/ha). The number of treatment combinations and number of replications within a soil mapping unit varied, depending on the available land area within a specific soil-mapping unit. Corn grain yields increased with increased irrigation at both sites. There were significant differences in the yield response to irrigation among the various soil-mapping

units, with greater yield response on some soils as compared to others. However, the difference in yield response to water applied is most likely not always a function of the soil water characteristics, because some soils are more productive than others for the same amount of water applied. Rather, the difference in yield response to water applied was probably caused by a combination of irrigation frequencies and different water holding capacities for each soil type. The irrigation set-up adopted was to schedule based on four sets of tensiometer under each center pivot. Where the ideal condition would be to control the irrigation for each soil-mapping unit.

Drawbacks of response functions

The problem with crop response curves is that the curves are usually either field or plot averages, and are subject to temporal weather variability (such as rainfall distribution, and water demand). Traditional production functions are not able to predict or simulate the temporal distribution of water content during the crop growth period, nor the spatial variation in water content in a field. These functions are also empirically fitted. To give more theoretical weight to production functions, Martin et al. (1984) incorporated physically defined parameters such as soil water capacity and availability, and evapotranspiration. These functions related crop yields to gross irrigation requirements. Evaluation of these functions gave good representations for the limited test data used.

Alternative crop yield-water relationships

A site-specific irrigation schedule and a model that simulates the effects of water stress on crop yield can be a viable solution for the evaluation of yield response to water stress. Timlin *et al.* (2001) used crop yield maps combined with a water budget model to

determine water holding capacity (WHC). This methodology used a simple water budget to estimate the yield based on the relative transpiration ratio when the other factors (rainfall and potential evapotranspiration) of the water budget were known. The model varied the value of WHC over the field to minimize the sum of squares errors between estimated and mapped yield values. The estimated WHC contour map from the model was similar to the map of measured WHC obtained from collected soil cores. The authors noticed that multiple years of yield data were required to give stable results for estimated water holding capacities.

Models such as CROPWAT (Smith, 1992) can be used with information about the crop, soil, climate, and irrigation system (efficiency) to maximize water management over time and space. Another irrigation scheduling model- ISM (George *et al.,* 2000) can be used to prescribe the amount of water application for specific areas in the field given a certain level of information available. CROPWAT and ISM are able to estimate the effect of deficit irrigation on yield using water stress relations. The effect on yield response to water stress is caused by either limited transpiration or evapotranspiration (Hanks, 1974; Doorenbos and Kassam, 1979). Doorenbos and Kassam (1979) assume a maximum yield that is reduced by some limiting factors, in this case water deficit. This method of accounting for the effect of water stress on the yield is also used in crop growth models such as the EPIC and DSSAT (Williams *et al.*, 1989; Ritchie, 1998). Either way, these relationships have been largely used to estimate water stress caused by deficit irrigation (Shani and Dudley, 2001; Fabeiro, *et al.,* 2002).

Cavero *et al.* (2000) evaluated two models (EPICphase and CROPWAT) that simulate the effects of water stress on crop yield. Data were collected from three field

experiments, one sprinkler irrigated and two flood-irrigated, managed to create continuous water stress in a semi-arid environment. Comparison of the two models indicated that there is no advantage in using one or the other in terms of yield reduction calculation due to water stress. However, the evapotranspiration model in EPICphase gave better estimates of evapotranspiration. Nevertheless, if an accurate ET model were used, the two models were expected to obtain similar results.

Economic advantages of site-specific irrigation

Does yield response to site-specific treatment demanded by spatial variability of the soil provide enough economic return to pay the extra cost of site-specific application? Lowenberg-DeBoer (1999) evaluated the risk of adopting site-specific management of P and K. Three treatments were adopted (whole field, grid based, and by soil type) and the results showed the potential for precision agriculture to reduce the risk of low-income distribution. The treatment by soil type had a higher average net return compared to uniform application. However, this was a preliminary model tested at a particular location (Eastern Corn belt) for a particular data set. Additional work is needed to develop a general framework for management unit evaluation at different soil and weather conditions.

Feinerman and Voet (2000) extended a model first developed by Thrikawala *et al.* (1998) which evaluated the size of management unit and efficiency of fertilizer application. The Feinerman and Voet (2000) model proposed to address the effect of size and number of management units to reduce the variability of infiltration rate. Their analysis suggested that utilization of site-specific farming technologies did not guarantee water savings. Although the model introduced some important factors such as the use of

net return as a tool for the decision process, the model was theoretical and most likely could not be used to provide an actual prescription map of the field that would be useful for farmers. Seidl *et al.* (1999) used a crop growth model/GIS linkage to create prescription evaluations of optimum seed population and variety selection. The framework was based on yield estimation through the field, followed by estimation of net return over 21 years of simulation; the final solution was a prescription map for the field. Roberts *et al.* (2000) developed a general framework to evaluate the returns of variable rate nitrogen application. English *et al.* (2001) extended the framework for use in a field with multiple management zones. They concluded that the final decision of whether to use variable rate (site-specific) over uniform rate varies from field to field, depending on the spatial variability of the soil and the yield response variability among the management zones.

Similarly, the field layout suitable for site-specific irrigation should present an economic advantage over the traditional uniform management. The benefits of site-specific irrigation management should be compared with the extra expense involved in creating a site-specific application of water. Site-specific irrigation management will not likely be an economically viable practice everywhere; greater benefits will be expected for fields with high spatial variability in soil properties. Probably the greatest advantage of site-specific irrigation management will be improved water efficiency and environmental benefits. Nevertheless, studies have shown the economic potential of site-specific irrigation management; where this technology was used, it promoted an increase on gross income of $165/ha compared with conventional uniform management for potatoes grown in Idaho (King *et al.*, 2002).

CHAPTER 3

FRAMEWORK CONCEPTUALIZATION

The literature review confirmed the needed for a framework to evaluate the effects of site-specific irrigation on the production process. A procedure to delineate and evaluate management units for site-specific irrigation management was proposed to address the problem of field variability. Figure 3.1 gives an overview of the procedure.

First, the soil properties relevant to irrigation management must be identified spatially. Second, the soil information is transferred to GIS layers. Depending on the quality of information available, the identification of sub-areas is performed in one of two ways: a) if soil maps are available, the sub-areas that are identified are limited to the map's spatial resolution; b) if the soil information is available from samples, an interpolation technique is used to extrapolate the data to the whole field, with contour lines delineating soil properties in a particular layer. Any areas with constraints for irrigation are identified and those areas are excluded from future analysis. At this point, a map with the highest-resolution contained the minimum management units (MMUs) is created. Third, a merging algorithm is used to create the different irrigation management layouts. Finally, the resulting management units (MUs) are evaluated through an economic response analysis.

The proposed framework is intended to be general and portable to different soil and weather conditions and uses a GIS (ArcMap v8.1) platform combined with a yield and irrigation-scheduling model. The model estimates yield reduction due to irrigation amounts and water stress for each sub-area. Net returns are calculated for a given area

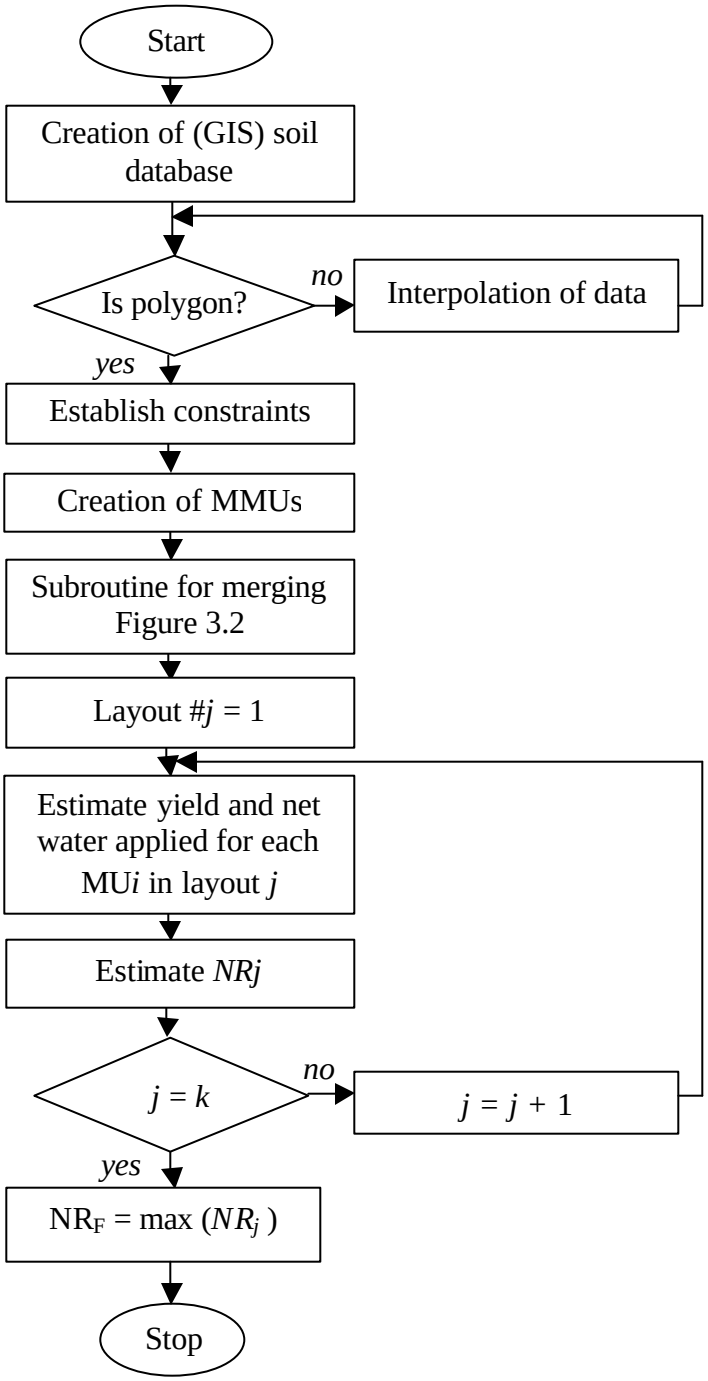


Figure 3.1. Flowchart of how information is processed to determine the optimum site-specific irrigation management layout *j* that maximizes net returns (*NR*).

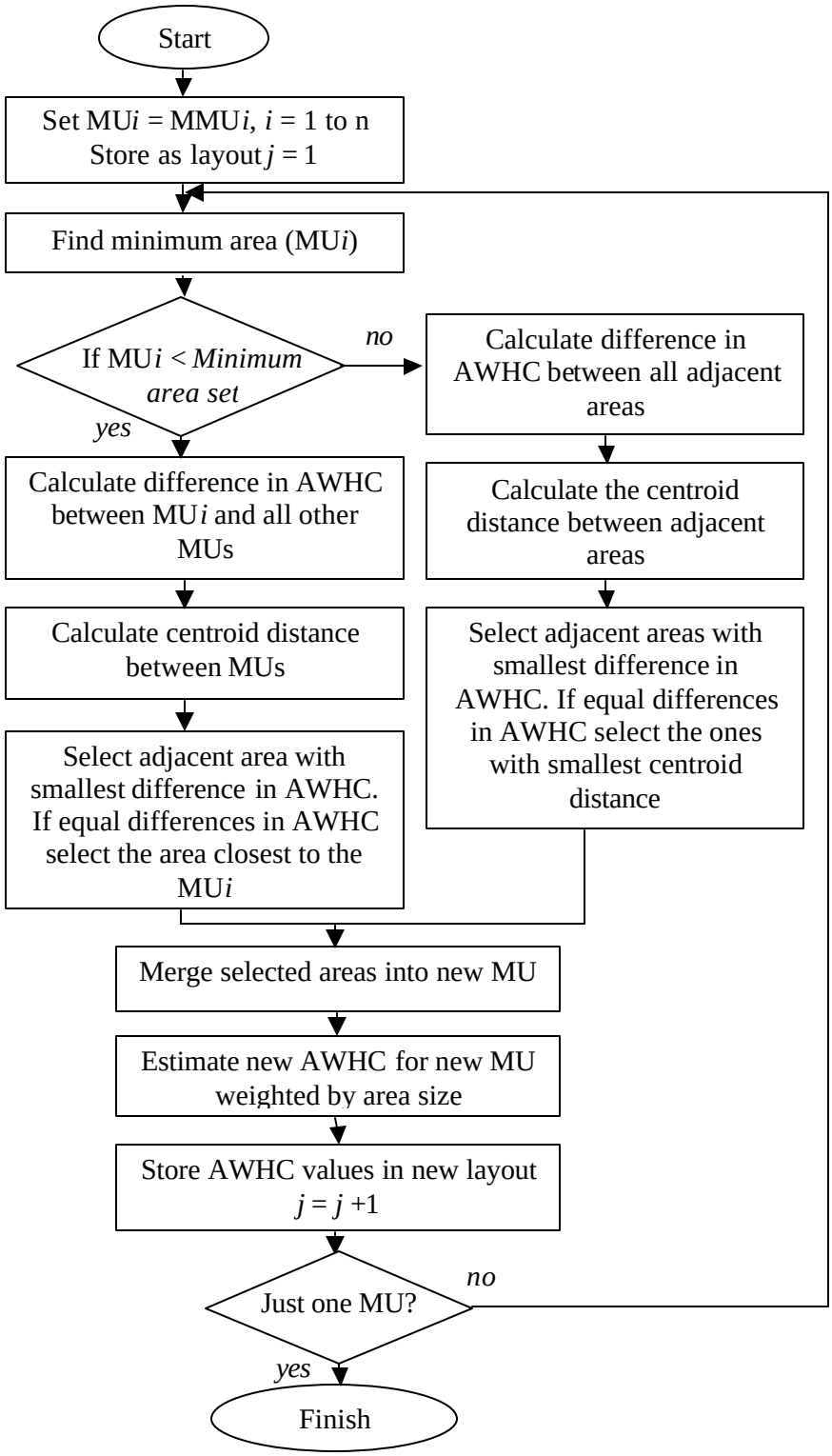


Figure 3.2. Schematic of how the sub-areas are merged in the decision-making framework.

and totaled for a given layout. The framework tests the different field layouts, from minimum management units to the whole field. The selected optimum layout is the one that yields the highest net return. The selected layout then can be displayed with GIS to help the farmer correctly implement the irrigation units. Each section of figure 3.1 is discussed further in the following sections.

Creation of GIS database

Soil properties including water-holding capacity, drainage rate, rooting depth, and fertility have been identified as major causes of spatial yield variability (Khakural *et al.*, 1996; Paz *et al.*, 1998; Irmak *et al.*, 2001). Several researchers have studied the effects of soil variability on yield variability, and emphasized site-specific input application as a way to minimize the variability (Mantovani *et al.*, 1995; Beltrao and Asher, 1997; Thrikawala *et al.*, 1998; Seidl *et al.*, 1999; Lowenberg-DeBoer, 1999; Feinerman and Voet, 2000). Based on these studies and equations found in irrigation system design books (Cuenca 1989; Martin *et al.*, 1990), the following properties were included for consideration:

- Available water holding capacity (texture, soil profile)
- Infiltration (texture and structure)
- Depth (soil profile)
- Slope (topography)
- ET (exposure direction, texture, structure)
- Crop (water consumption, salinity stress, water stress +/-)

These properties are the most relevant for establishing an irrigation schedule that answers the two big questions of irrigation – when and how much to irrigate. These

decisions affect crop growth and yield. Yield response to irrigation at a site-specific level requires site-specific information about properties on the list. With a few assumptions, some of these properties can be held constant over the field. For example, selection of the minimum infiltration rate of the soil for system design should satisfy the infiltration conditions for the whole field. Other soil properties such as electrical conductivity of saturation extract or limited soil depth must be known, to ensure that these factors will not restrict the potential growth of the crop. When such restrictions to production occur, constraints to the area where the restriction occur are established. However, among those properties, available water holding capacity (AWHC) and soil depth have a greater impact on the site-specific irrigation schedule than the other factors, because these two properties determine the amount of soil water available to the crops. These two properties were considered the basis for delineation of the different management units. The proposed framework was tested with actual values of AWHC and soil depth. The AWHC is the amount of water available that is held in the soil per increment of soil depth, and is defined as the amount of water held between the soil water potential that defines field capacity and the permanent wilting point (NRCS, 1997).

Interpolation of data

If the soil information is presented as a sampling survey, the data points in the layer can be interpolated to generate a continuous variation throughout the field and values can be assigned to points not sampled. The spatial analyst functions of the GIS have several interpolation methods such as Inverse Distance Weighting, Spline, and Kriging (www.esri.com). The geostatistics interpolation techniques are often preferred for studies of soil physical characteristics because it considers the spatial correlation of

the data. It is based on regionalized variable theory and uses semi-variance to identify two points in the field that are spatially independent (Upchurch and Edmonds, 1991). Interpolation techniques can be used to delineate zones (isolines) that are spatially independent of each other, i.e., points within the contour lines have some dependency and consequently less variation (figure 3.3).

If the desired soil property (e. g., AWHC) is not directly available, it can be inferred from one or two soil properties that are related to it. Evans *et al.* (1996) inferred AWHC from soil texture, and soil texture from percentages of sand, silt, and clay. After each layer has been stratified and divided within contour lines, the layers can be overlaid. Each resulting layer contains all the attributes of the other layers, as well as the contour lines. The intersection of the lines delineates the sub areas in the field that represent the minimum management unit (MMU). The MMU is the area with minimum variation for the property under consideration (e. g., AWHC). Illustrated in figure 3.3 are two layers, one with the water content on a mass basis and the other with soil bulk density; these two layers were interpolated and overlaid to obtain a third layer of volumetric water content from which AWHC can be estimated.

Soil map

If the soil information is presented in maps, the soil units of the maps will represent the natural soil boundaries and the respective management units. In this case, the level of detail of the map limits the resolution, so a finer scale map will provide better resolution. Sadler *et al.* (1998) reviewed spatial resolution for site-specific management for the Southeastern U.S. Most common soil survey maps are made at 1:20,000 resolution. From the research reported by Sadler *et al.* (1998), the most commonly

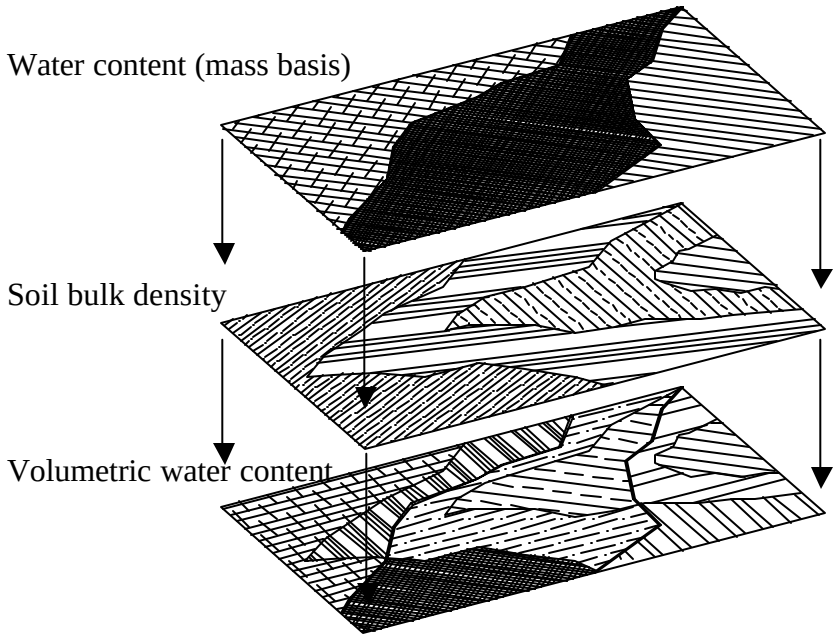


Figure 3.3. Illustration of overlay of layers and creation of minimum management units for site-specific irrigation.

accepted upper limit for grid size in site-specific management was about 100 m x 100 m, though finer resolution proved necessary for the correct characterization of the spatial variability. Sadler *et al.* (2000b) compared the variation in water use and stress on corn within and among soil map units. They concluded that reliance on a single soil description for an entire soil map unit, even at the scale considered 1:1,200 (Order1), was not adequate to explain the field variance. Franzen *et al.* (2002) reported that at least Order 1 soil survey scales were necessary to develop nitrogen management zones for site-specific agriculture.

Establishing constraints

Any serious constraint to irrigation (e.g., rock outcrop) must be identified and the area excluded from future analysis. This step is important because it will avoid further

data analysis for areas that have inherent poor yield and most likely will not be economically viable for irrigation, thus saving computation time and database storage capacity.

Based on the values of the properties in the GIS layer, some irrigation constraints can be established in advance. For example, the soil textural class layer may indicate that part of the field may only be flooded for rice production, or the soil depth layer may suggest that shallow bedrock occurs near the surface of the ground. Presented in table 3.1 are examples of soil depth restrictions for irrigation management as reported in the guidelines for land evaluation for irrigation (FAO, 1979). The level of suitability for irrigation of some of these properties is associated with the specific crop, e.g., different crops have different root depths. Vink (1975), FAO (1979), and Dent and Young (1981) provide more information on suitability for irrigation and land use surveys.

Creation of minimum management units

The resulting map of AWHC, after removal of the areas not suitable for irrigation, represents the map from which the minimum management units (MMUs) are delineated. The MMUs are created by identification of the smallest value of the AWHC difference across the field. The map with the MMUs has the highest level of resolution available and corresponds to the first layout of completely site-specific irrigation management. Areas with the same AWHC that occur at different locations in the field and are not adjacent, should be considered as different minimum management units. This is necessary because each will require separate control valves and pipelines to deliver water to the different locations in the field.

The MMUs can be represented either by polygons or cells, depending on the data

Table 3.1. Soil depths that limit irrigation potential (FAO, 1979).

Critical Limits of Soil Depth	Suitability
Over 200 cm	Highly suitable
100-200 cm	Moderate suitable
50-100 cm	Marginal suitable
25-50 cm	Marginal Not suitable
0-25 cm	Not suitable

format of the GIS file. Either way, the MMU is represented by an individual record (row) in the database.

Merging of sub-areas into a layout

Some of the original minimum management units may then be grouped with surrounding minimum management units, forming a unique new average management unit. The objective is to verify if there is any economic advantage of an alternative layout between the minimum management units and the whole field as a uniform management unit. The following hypotheses were tested:

1. There may exist another layout that gives higher total net return than the one with MMUs from the soil-mapping units.
2. Combining adjacent polygons (MMUs) that have similar mean average properties reduces the cost of implementing the management unit (MU), thereby potentially increasing the net return (Note: a MU is composed of one or more MMU).
3. Alternatively, combining adjacent polygons (MMU) that are similar may reduce the yield for the underirrigated portion of the MU after an average

input for the new MUs has been applied. A reduction in the yield reduces the gross income, decreasing the total net return.

To test the above hypotheses, an interactive algorithm that combines the adjacent polygons (MMU) into larger polygons units (MU) was developed. The new polygons thereby correspond to new possible management units in the field. These new management units have a higher within-unit variability compared with the original minimum management units.

The procedure for merging of the sub-areas is shown in figure 3.2. If a sub area in the field is smaller than a user-selected minimum (usually 1 ha), this smaller area is the first selected for merging. Otherwise, merging begins with the adjacent sub-areas that have the smallest difference in AWHC. The algorithm calculates the difference in AWHC of each sub-area for a given layout. The distance of the center of each sub-area to the center of others sub-areas is also calculated. Based on this information, the algorithm makes the selection of two adjacent sub-areas for merging. The selected sub-areas are merged and a new mean available water holding capacity is calculated as an area-weighted average from the previous sub-areas. This forms a new field layout.

Adjacent areas will continue to be merged, one after another, until the whole field has been merged together as a single management unit (uniform irrigation). Several layouts (1, 2,..,k*)* are formed, ranging from the highest-resolution site-specific layout to the uniform management layout, with other combinations between these two layouts. The total net return is calculated for each layout *j*. The user selected layout is the one that maximizes net return.

The decision to first merge areas smaller than a pre-defined minimum is because small areas are most likely to have a higher cost of implementation. An area of 0.5 to 1.0 ha is usually the minimum considered for irrigation (FAO, 1979). For a given crop yield (Y), cost, and price of product (PP), there is a minimum required area to cover the costs. The minimum area (*Area*) to cover the costs can be calculated as:

$$Area \times Y \times PP = costs$$

$$Area = (Costs)/ Y \times PP \quad (3.1)$$

Illustrated in figure 3.4 is the merging of sub areas from minimum management units to the whole field. In this example, the field is originally divided into eight management units, and it takes eight steps (j = 1 to 8) to merge all sub areas into one area that corresponds to the whole field area.

Estimated yield for site-specific irrigation

Site-specific irrigation systems are assumed to be designed to apply the optimum water application to each of the management units in the field, with the proper amount at the proper time. However, when a uniform irrigation application is made for different management units with spatial variability, parts of the field do not receive the correct amounts of water because the water balance is not the same for the whole field. This improper water balance causes water stress or overirrigation in some parts of the field and prevents maximum yield. In reality, irrigation applications are often not uniform even within the management unit, because of limitations in the irrigation system. Santos (1998) developed a general analytical framework for defining criteria for objective comparison of alternative irrigation systems and uniformity of application compared with yield response. Comparable yields and infiltrated water were obtained when comparable

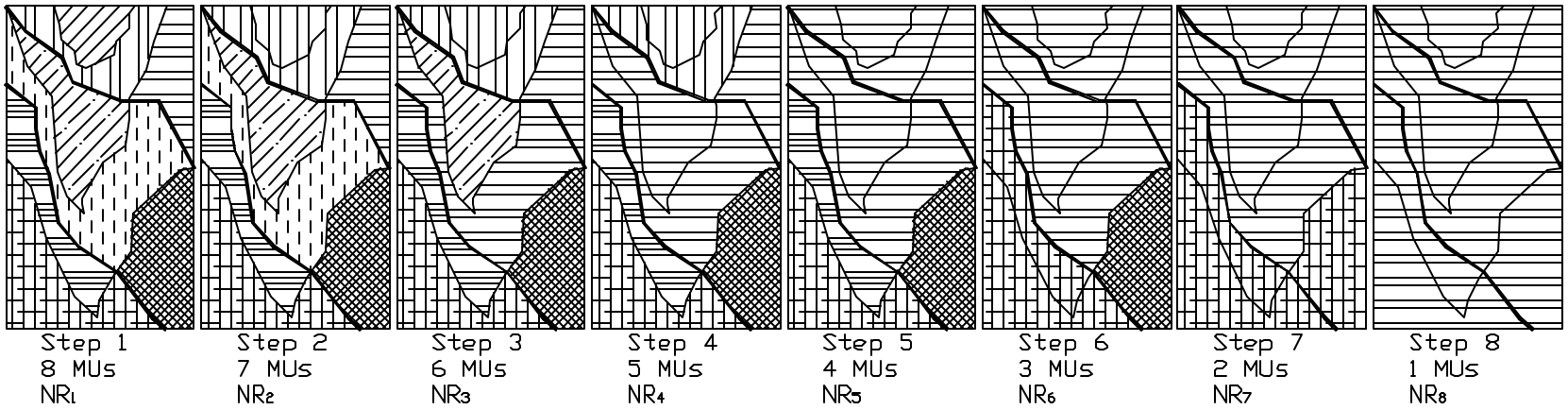


Figure 3.4. Layouts develop by successive merging of MU areas, and ranking of net returns.

assumptions of water application uniformity and fraction of the field area adequately irrigated were assumed.

For this study, uniform application inside a management unit is assumed. This analysis is based on the net irrigation application. Issues related to adequacy and uniformity of application were not considered in this analysis, which is to decide if two management units should receive the same or different irrigation management treatments. The yield was estimated using a yield response to water function detailed in the next chapter; this function assumes maximum yield in case there is not a limiting factor.

Whichever model is selected for estimation of yield due to site-specific irrigation, it must contain at least two parts. First, the model should include an irrigation-scheduling component to estimate water demand time and amount. Second, the model should contain a yield estimation component that uses the prescription from the irrigation schedule to estimate crop yield. The desired outputs should be the expected yield and the amount of water (net irrigation) used to obtain that yield.

Estimated net-return for site-specific irrigation

The decision of whether to use site-specific irrigation management (several management units) versus uniform irrigation management (one management unit that covers the whole field) is based on whether a producer will realize an economic advantage. Thus, the decision to implement site-specific irrigation is dependent not only on the soil variability but also on technology cost.

One major criterion for deciding how to divide a field into management units is expected crop yield. As previously discussed, yield can be estimated as a function of

weather and water allocation that varies according to soil properties (Howell *et al.*, 1990; Timlin *et al.*, 2001). Thus, yield (*Y*) can be estimated from the function:

$$Y = f(\vec{w}, \vec{s}, \vec{I}) \quad (3.2)$$

where: $\vec{w}$ = vector of seasonal weather,

$\vec{s}$ = vector of the soil properties, and

$\vec{I}$ = vector of seasonal irrigation amounts.

A second important decision criterion is profit, which is defined as total revenue minus total cost. Revenue is the income from the crop yield; the total cost is divided into fixed and variable costs. Fixed costs refer to those that do not change with the level of production, such as investment costs. Variable costs refer to the cost of resources that are used over the season and change with the amount of output produced in the short run. For irrigation, these costs are electricity or fuel to pump water, labor, and the water. The total net return for the whole area (*NR*) can be expressed by the general equation:

$$NR = A \times Y \times PP - (I \times PW) - VC - FC \quad (3.3)$$

where: *Y* = total yield, as a function of the inputs (kg/ha);

A = area of production (ha);

PP= product price ($/kg);

I = total water applied during the season (mm),

PW = the price of water per depth of water ($/mm),

VC = variable costs other than water cost ($),

FC = fixed cost ($).

Net return is a highly variable function of weather (through yield) and the economy (through price). If we assume that the economy is assured of short-term stability, or that the grower has locked in a fixed price, and that crop yield and irrigation schedule are both dependent on daily fluctuations of weather patterns, weather pattern causes most of the variation in the net return results. The above net return equation is for a point source application. A modification is required to allow variable rate application over several management units in the field. Recalling that yield response is also variable for the different management units, the net return for a site-specific case is:

$$MUNr_{it} = A_i \times Y_{it} \times PP - (I_{it} \times PW) - VC_{it} - FC_{it} \quad (3.4)$$

where: $MUNr_{it}$ = Net return for the sub area i for year t (\$) i =1 to n, t = 1 to m;

A_i = MU_i area of production (ha);

Y_i = yield on sub-area i for year t, as a function of the inputs (kg/ha);

I_i = water applied during the season (mm), on each sub-area i for year t;

VC_i = variable costs besides water cost in sub area i for year t;

FC_i = portion of total fixed costs in sub area i for year t;

Other variables already described.

The net return is totaled for the whole field for a particular layout j. In the event that the layout (number and size of management units) changes, a new total net return must be calculated. For this study, water is assumed available and plentiful enough for each management unit. The total net return for the field for a given year (T) is estimated as:

$$Nr_{jt} = \sum_{i=1}^{n} MUNr_{it} - V_j \quad (3.5)$$

where: Nr_{jt} = Net return for particular layout j at year t (j = 1 to k);

$MUNr_{it}$ = Net return for the sub area i at year t, within layout j ($);

V_j = annualized costs for (VRI) application for layout j ($control unit × #MU).

The variable rate input (VRI) cost that was not covered in other previous studies (Thrikawala *et al.*, 1998; Feinerman and Voet, 2000) should be included as one way to penalize the net return function when trying to optimize the inputs (cost of being site-specific). This cost is equal to the cost of the control units times the number of management units for a particular layout. The formulation above is still flexible, and multiple inputs and outputs may be incorporated (such as extra labor and equipment), as was done for this case study. Finally, the average net return for a particular layout j (ANr_j), over the years can be calculated as:

$$ANr_j = 1/m \times \sum_{t=1}^{m} Nr_{jt} \qquad (3.6)$$

where: Nr_{it} = Net return for layout j at year t ($);

m = number of years of weather data.

CHAPTER 4

FRAMEWORK IMPLEMENTATION

The conceptual framework introduced in the previous chapter was implemented for a case study of site-specific irrigation – staked tomatoes under a drip irrigation system. The selected crop was fresh-market tomatoes; because of the high value and the sensitivity of the crop to water stress, the crop was well suited for the case study.

Site description

Available water holding capacity (AWHC), which is one the main properties in the analysis, is directly correlated with spatial variation of soil texture and soil depth. Sites with great variability in soil texture in the Tennessee state are found close to the Mississippi river, and in fields located in east Tennessee. The selected site was located in Cocke County (35°59'40" N, 83°10'30" W) in east Tennessee (details in Appendix C). The field consisted of 16 hectares (40 A) that had been previously cropped with soybeans. The soils in the field were grouped as bottom lands consisting of recent alluvium, and subject to flooding and inundation. The soils were originally formed from micaceous rocks such as gneiss and granite, and contain large quantities of mica flakes. Taxonomic classifications for the soil series referred to in this study are included in Appendix B (http://ortho.ftw.nrcs.usda.gov/osd/osd.html).

Soil data

An intensive soil characterization and mapping was carried out on the selected field. This characterization was strongly influenced by the site landscape and the existing soil series as defined by USDA-SCS. The sample intensity and design were not constrained to existing soil mapping surveys. Some soil series not present on the existing

USDA-SCS map were found in the field. Soil scientists from The University of Tennessee took samples using a soil bucket auger: the pattern and intensity of sampling were based on the complexity of the landscape and observable soil features at various locations in the field. Each sample profile was examined for identifiable features and profile characteristics as described in the respective soil series survey (NRCS, 2002). The representative sampling area ranged from 0.1 to 0.4 ha (0.25 to 1.0 A). The position of each soil sample location was recorded using a Trimble AgGPS 132 (Trimble Navigation, Sunnyvale, CA) differential global position system (DGPS) receiver.

Following sample completion, soil-mapping unit boundaries were delineated by outlining the logical soil breaks on the landscape. The soil boundaries were drawn on the landscape by driving an all-terrain vehicle along the boundaries; a DGPS unit was used to record the position and to log the data into a palm-top computer. This survey method resulted in a more precise estimation of the soil-mapping units than could be obtained from Order 2 county soil surveys. The intensity of the soil sampling was approximately equal to the 1:7,920 scale traditionally used in the United States for individual soil mapping for conservation planning, allowing delineation of areas of 0.2 to 0.4 ha (0.5 to 1 A). As discussed above, the source soil of information match in the category of soil maps as discussed in chapter 4.

The spatial soil data were imported into ArcMap 8.1, which was used to create a map with each soil map unit represented by a polygon that had a label of the soil-mapping unit assigned in an attribute table. The map with the respective soil-mapping unit legends is shown in figure 4.1.

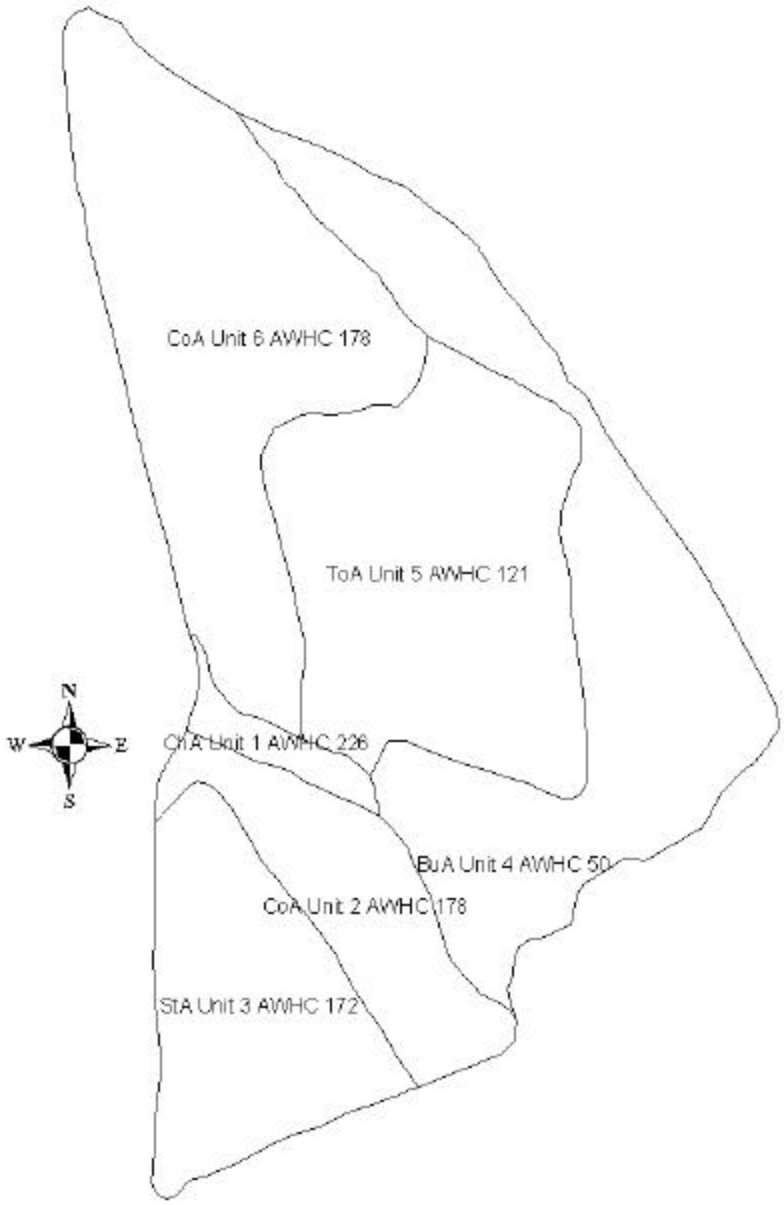


Figure 4.1. Intensive soil-mapping units for the field in Cocke County that was used in the case study.

Five soil series were identified in the field: Chewacla, Congaree, State, Toccoa, and Buncombe. The descriptions of these soil series according to the official soil series description of the USDA-NRCS soil survey division are given in Appendix B (http://ortho.ftw.nrcs.usda.gov/osd/osd.html).

The five soil types in the field formed six minimum management units. One soil type (Congaree) occurred twice in different parts of the field (figure 4.1). After each soil type was identified, physical characteristics – specifically those suited to the framework analysis – were searched to create a database (table 4.1). The soil information was gathered from the Soil Survey Staff (1955), Longwell *et al.* (1963), and consultation with faculty members who surveyed the field (Denton, 2003). The complete attribute table used in the analysis is found in Appendix B.

Establishing constraints

From the high resolution soil map, the database was searched for any possible restrictions to irrigation. The possible constraints were found to be topography, infiltration rates, and minimum soil depth.

Topography is considered a constraint when it limits some areas in the field to the use of specific irrigation methods; specifically topography affects irrigation suitability based on slope, micro-relief, macro-relief, and position.

Slope is a more significant constraint for gravity or surface irrigation than for other irrigation methods. For site-specific irrigation, where a pressurized system is usually used, slope is typically not a limiting factor. However, slope may increase operation and maintenance costs. For center pivot and linear move systems, the slope has a greater effect on water erosion and water infiltration. For drip irrigation, a restriction

Table 4.1. Soil physical information with AWHC adjusted to 1-m soil depth.

Soil Series	Horizon Texture	Layers m	Depth m	Saturated mm/h	Bulk Density	θμ (%) 33.7kPa	θμ (%) 1519.8kPa	TAM mm/m	Layer m	Water Depth mm	WHC mm/m
Congaree	Fine silt loam	0-0.18	0.18	56.9	1.33	18.3	5	176.89	0.178	31.45	
	Silt loam	0.18-0.53	0.35	143.3	1.19	21.2	5.7	184.45	0.356	65.59	
	Silt loam	0.53+	1.00	116.6	1.28	17.6	4.1	172.8	0.467	80.63	
								Total	1.000	177.67	177.67
Chewacla	Silt loam	0-0.18	0.18	385.3	1.36	27	11.3	213.52	0.178	37.96	
	Silt loam	0.18-0.51	0.33	403.6	1.51	24.6	10.1	218.95	0.330	72.30	
	Silt loam	0.51+	0.25	160.5	1.44	26.9	10.6	234.72	0.492	115.48	
								Total	1.000	225.74	225.74
Buncombe	Sand	0-1.52	1.52	-	-	40.00	60.00	50.00	1.000	50.00	
								Total	1.000	50.00	50.00
State	fine sand loam	0-0.25	0.25	-	-	130.00	210.00	171	0.254	43.43	
	clay loam	0.25+		-	-	140.00	210.00	172	0.746	128.31	
								Total	1.000	171.75	171.75
Toccoa	sandy loam;	0-0.25	0.25	-	-	-	-	121	0.254	30.73	
	sandy loam;	0.25-0.61	0.36	-	-	-	-	121	0.746	90.27	
	fine sandy loam;	0.61-0.86	0.25	-	-	-	-	Total	1.000	121.00	121.00

based on slope has not been established, but for sprinkler irrigation, a limit of 35% has been established (FAO, 1979). In the field used in this case study, the slope in the area varied from 0 to 3%, so based on slope criterion all of the area was suitable for site-specific irrigation.

Micro-relief refers to minor surface undulations, and land grading is the most common development required for smoothing the area. Micro-relief often presents a problem with surface irrigation systems. Macro-relief is related to the correctable deficiencies on land that have a smooth, uniform slope, but with complex topography where slopes change frequently in gradient and direction. Macro-relief is important as a consideration for the cost and design for the area, and how the irrigation system should be placed in the field.

Position relates location of sub areas in the field to water source, drainage outlet, and size and shape of the areas. It is normally accepted that areas under 0.5 ha were not to be regarded separately for irrigation, with this limit often being increased to 1 ha (FAO 1979). However, in this framework, the general relation given in equation 3.1 gives the area restriction size. The small area in the field MMU 1 was considered for merging with other areas within the field, which made this area more profitable.

Infiltration rates could restrict the use of an area to a particular irrigation method. For instance, values below 0.15 cm/h may be usable only for flood irrigation (such as a rice field). However, 0.15 cm/h is the minimum value of infiltration rate for most other crops. The minimum infiltration rates for the soil types identified in this case study were above this threshold value, and the sub-areas were not constrained by the type of irrigation selected.

The minimum soil depth can produce an inadequate rooting system and limit total water availability. The effective rooting depth is dependent on the selected crop; for tomatoes, the expected effective root depth is one meter. General guidelines to determine critical limits of soil depth are presented in table 3.1. The soil depth for the identified soil-mapping units were greater than the required effective root depth for tomatoes, so soil depth did not present a constraint within the selected field.

Each mapping unit formed the minimum management unit, since this was the highest resolution of information available. The map of the field, with the MMUs delineated, is presented in figure 4.1. The label format is the soil type abbreviation, followed by the legend corresponding to the ID of the MMU, and the value of the available water holding capacity in mm/m.

Merging management units

Merging of the MMU was in accordance with the procedure described in Chapter 3 (figure 3.3). To implement the algorithm, the data must be presented as a feature class polygon shapefile. Also, the areas that have the same AWHC but occur at different sites in the field must be independent polygons. If not, a procedure is necessary to separate these areas (Appendix B). Even though the areas have the same AWHC, the areas cannot be treated as the same unit when the areas are not contiguous.

A site-specific irrigation schedule (SSIS) toolbox was added to the GIS document to implement some of the functions necessary for the analysis. On the map layer that contains the management units, attributes for area and the X and Y coordinates of the centroid were created in an attribute table. The values for these created attributes were calculated automatically by an algorithm that was included as part of the SSIS toolbox.

The computation of the area was important for the selection of possible sub-areas smaller than the user pre-defined minimum area. Also, the calculation of the new AWHC was based on the average AWHC weighted by area. The X and Y coordinates are used in a Pythagorean distance calculation of the centroid that is used as one of the decision criteria in the merging algorithm.

Equation 3.1 is used to determine the minimum area required to recover the cost of site-specific irrigation (NR = 0) for tomatoes, given the average price of $32.47/cwt (table 4.2), yield of 453.75 cwt/A, and estimated total costs of $3,752.80/A (from the modified tomato budget, Appendix B). The minimum area required to cover the costs is:

$$Area = (Costs)/ Y \times PP$$

$$Area = (3{,}752.80)/ 453.75 \times 32.47 = 0.25 \text{ Acre } (0.10 \text{ Hectare})$$

This is the minimum value; the required area would be larger when the cost of harvest, set-up, headlines, fuel, and control units would be added. Also, maximum yield was assumed for the area, as well as no other restriction to yield. High yields of tomatoes, associated with high prices, make even small areas (such as 0.10 ha) profitable for site-specific irrigation systems. For crops less profitable than tomatoes, the minimum area requirement would be larger.

For the minimum price of $20.00/cwt (table 4.2), and 60% of yield (0.6 × 453.75 cwt/A), and higher cost $7,719.97/A (table 5.2), the required area is:

$$Area = (7{,}719.97)/ 272.25 \times 20 = 1.41 \text{ Acre } (0.57 \text{ Hectare})$$

Given these two extreme values, management unit 1 was considered large enough to be used for irrigation, even though it has only 0.29 ha.

Table 4.2. The year-to-year observed prices, the price index, and the present price values for 2001 dollars.

Tomatoes in TN			Price Received			Adj. Index	Avg. Price
Year	Yield/acre	Production	Avg. Price	Index	Index	Spliced	$/cwt
	cwt	1000 cwt	$/cwt	base=1977	base=1992	base=1992	base=2001
1971	120	264	10.8	59		44	32.37
1972	140	308	11.1	65		48	30.20
1973	110	253	19.9	76		56	46.31
1974	135	284	17.4	81		60	37.99
1975	130	312	23.9	92		68	45.94
1976	140	350	13.1	91		67	25.46
1977	110	385	26.6	100		74	47.04
1978	105	441	26.3	105		78	44.30
1979	100	370	23.2	110		81	37.30
1980	110	407	21.2	113		84	33.18
1981	120	516	23.5	136		101	30.56
1982	125	538	23.1	126		93	32.42
1983	100	400	20	130		96	27.21
1984	200	780	23	133		99	30.58
1985	280	1120	19	129	95	95	26.20
1986	210	903	20		92	92	28.48
1987	180	702	23		105	105	28.70
1988	180	702	28		104	104	35.27
1989	140	504	25		103	103	31.80
1990	200	860	24		102	102	30.82
1991	180	846	21		100	100	27.51
1992	160	720	21		111	111	24.78
1993	160	688	27		116	116	30.49
1994	230	920	27		109	109	32.45
1995	210	861	21		121	121	22.74
1996	215	796	24		111	111	28.32
1997	240	864	27		118	118	29.97
1998	250	850	38		123	123	40.47
1999	230	828	29		110	110	34.54
2000	290	1131	31		123	123	33.02
2001	165	495	20		131	131	20.00
						Average	32.47

An initial attribute called “Lay_W_1” was created. The original available water holding capacity values given in table 4.1 were stored in this attribute. The merging algorithm uses the selected records in the “Lay_W_1” and “AREA_M2” attributes to calculate the new AWHC. The new AWHC was stored in a new attribute column with the terminology “Lay_W_#” created automatically by the algorithm. The “#” represents the increased number of times the merging operation was performed and the number of MMUs that were originally on the soil map. The complete attribute table that was used by the algorithm of merging is shown in Appendix B. The layouts created by the merging algorithm are presented in chapter 5.

Estimating net water applied

Estimation of yield and irrigation amount was accomplished with a site-specific irrigation schedule that considers a site-specific water budget, combined with a simple water stress equation (Doorenbos and Kassam, 1979).

Site-specific irrigation schedule

The site-specific irrigation schedule uses a traditional water balance model with some modifications to fit site-specific requirements. A site-specific water balance can be expressed in terms of soil moisture depletion. Soil moisture depletion (*SMD*) in the root zone is defined as the difference between total soil moisture stored in the root zone at field capacity and the current moisture status. The water balance is given as:

$$SMD_{i;d} = SMD_{i;\,d-1} + ET_{ai;d} + DP_{i;d} - I_{i;d} - P_{i;d} \quad (4.1)$$

where: SMD = Soil moisture depletion, mm

ET_a = Actual evapotranspiration, mm;

DP = deep percolation, mm;

I = net irrigation amount, mm;

P = effective precipitation, mm;

d = time index, day; and

i = space index (sub area within a field).

The water balance at any point in time and space is also a function of water that moves beyond the root zone as deep percolation and is not accessible to the crops, and the amount of water that is made available either by irrigation or precipitation. If the water application was greater than the capacity of the soil profile for a MMU because it had been merged into a MU with a higher AWHC, the extra water was considered lost as deep percolation. The amount of the net irrigation usable was necessary to return the soil water profile to field capacity without losses in the system.

The portion of the total precipitation that becomes available for plant growth is called effective precipitation. The effective precipitation is dependent on the amount of water that infiltrates into the soil. The rate and quantity of water that infiltrates is a function of soil type, current water content, soil cover, surface drainage conditions (slope), and precipitation characteristics (volume and intensity). Effective precipitation is often computed as the difference between total precipitation and runoff. Runoff is estimated separately, usually using the NRCS curve–number method (Wanielista *et al.*, 1997). For simplicity, in this study effective precipitation was estimated as a constant fraction (0.7) of the total precipitation.

The available water holding capacity of the soil must be determined in order to define the amount of water available in the soil. The soil depth from which roots are effectively extracting water also affects the amount of water that can be used by the

crops. Several factors influence the effective root depth (R_d), including the crop and the soil profile. With these two parameters, AWHC and R_d, it is possible to estimate the total water availability of the soil or TAM (Total Available Moisture). However, it is not a good management practice to allow the water to be depleted to the lowest limit (permanent wilting point), and a Management Allowed Depletion (MAD) value between the upper and lower water content limits is used. Therefore, irrigation is desired when the *SMD* equals the Readily Available Moisture (RAM). The RAM is calculated as:

$$RAM_i = MAD \times AWHC_i \times R_{di} \quad (4.2)$$

where: *MAD* = management allowed depletion, fraction of available water that can be used without adversely affecting the plant and is defined as the ratio of readily available water to available water;

AWHC = available water holding capacity, mm/m;

R_d = effective root depth, m;

i = space index.

AWHC varies with soil type, as presented in table 4.1. A number of equations and tables are provided in textbooks and research reports for estimating the R_d over the growing season of a crop; the most common models are linear, crop coefficient, and sigmoidal (Cuenca 1989; Martin *et al.,* 1990). The soil depth at some points in a field can limit the maximum R_d, which may cause R_d to be site specific. In this case, the maximum R_d will be equal to the soil depth. For areas where the soil depth is not limiting, the R_d prior to reaching the maximum depth can be expressed by:

$$R_{di} = R_{dmin} + (R_{di;\,max} - R_{dmin}) \times (Dap/\,Dptm) \quad if\ (Dap/\,Dptm) < 1 \quad (4.3)$$

$$R_{di} = R_{di;\,max} \quad if\ (Dap/\,Dptm) \geq 1$$

Table 4.3. Tomato crop coefficients for the yield and irrigation schedule models.

Growth Stages[a]	Units	Initial	Development	Mid	Late	Total
Crop stage Lengths	Days	30	40	45	30	145
Crop Coefficients (Kc)	-	0.6	-	1.15	0.8	-
Rooting Depths	m	0.25	-	1	1	-
Depletion Levels, (MAD)	ratio	0.3	-	0.4	0.5	-
Yield Factors (Ky)	-	0.5	0.6	1.1	0.8	1.05

[a]Source: CROPWAT 4 version 4.3 (1998)

where: R_{dmin} = the minimum root depth for young plants, m;

$R_{di;\,max}$ = the effective maximum root depth, m;

Dap = the days after planting, day; and

Dptm = the days from planting to maturity (full cover), day.

i = space index.

The MAD coefficients are dependent on the crop ability to extract water at different potential energy levels according to the soil content and characteristic curve of the soil. These coefficients and the number of days required for each period of growth are presented in table 4.3.

The actual evapotranspiration (ET_a) equals maximum evapotranspiration demand (ET_m) when available soil water to the crop is adequate. However, when available soil water is limited, actual evapotranspiration is less than maximum evapotranspiration demand (ET_m). Available soil water can be defined by the fraction MAD to which the total available soil water can be depleted without causing ET_a to become less than ET_m. ET_a can be estimated as:

$$ET_a = K_s \times ET_m \qquad (4.4)$$

To determine the K_s (crop stress factor), a calculation of the soil water content is necessary to know the percent depletion of the soil at a given stage of the development of

the crop (figure 4.2). The soil moisture depletion can be calculated based on the water budget when the available water holding capacity (θ_{fc} - θ_{pwp}) is known.

The crop stress factor is estimated by the linear function as:

$$K_s = (TAM - SMD)/(TAM - RAM) \quad if \ SMD > RAM \qquad (4.5)$$

$$K_s = 1 \quad if \ SMD < RAM$$

Crop evapotranspiration (ET_c) can be estimated from reference crop evapotranspiration or reference evapotranspiration (ET_o) by using a crop coefficient K_c. Differences in leaf anatomy, stomata characteristics, aerodynamic properties, and even albedo cause the ET_c to differ from the ET_o under the same climatic conditions. Experimentally, crop coefficients (K_c) are determined as the ratios of ET_c/ET_o, thus $ET_c = K_c\ ET_o$ (Hatfield and Fuchs, 1990; Jensen *et al.*, 1990; Allen *et al.*, 1998). The K_c value can be estimated from research; in many cases, general values are given for a particular crop, e.g., table 4.3. The relation of ET_c/ET_o refers to conditions when water is adequate and unrestricted, and in this case ET_c is the maximum evapotranspiration (ET_m) for a given climate and crop.

ET_o can be estimated from weather data, evaporation pan measurements, or lysimeter measurements. A large number of empirical or semi-empirical equations have been developed for assessing ET_o from weather data. The most accepted method is the FAO Penman-Monteith (Allen *et al.,* 1998). The ET_o, according to the FAO using the Penman-Monteith equation, is the evapotranspiration rate from a reference crop surface not short of water. The reference surface is a hypothetical grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1}, and an albedo of 0.23. The use of other terms, such as potential ET, is strongly discouraged because of the

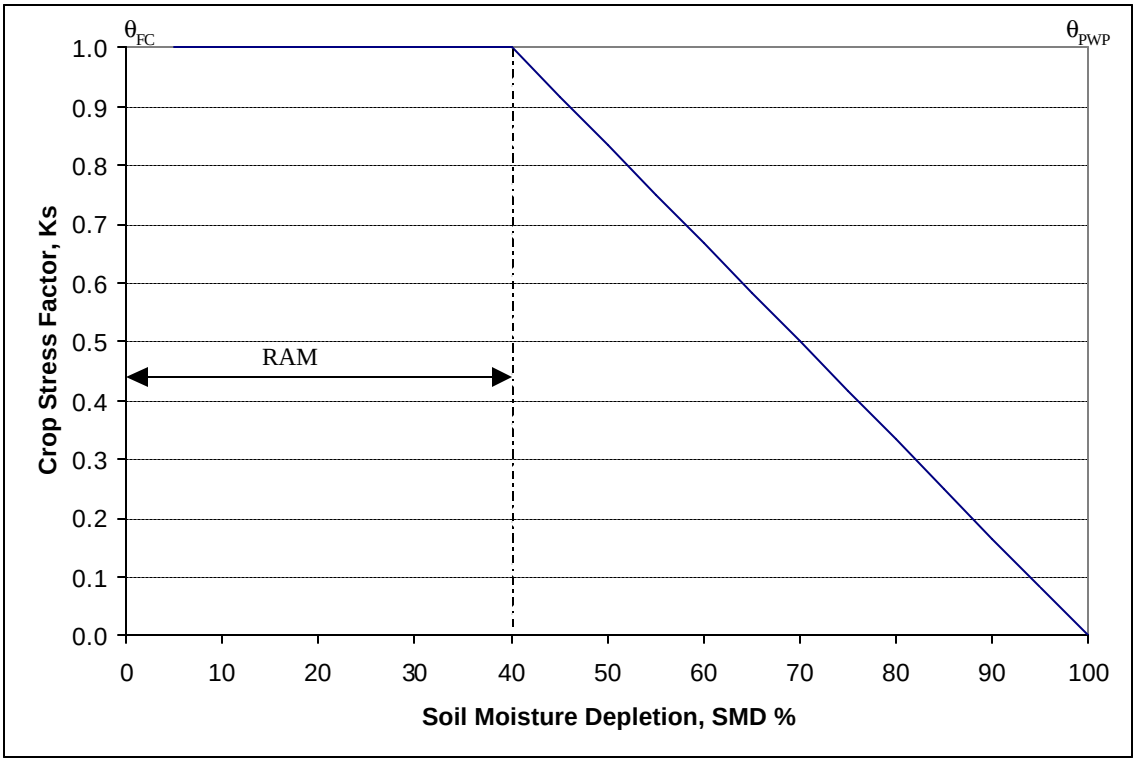


Figure 4.2. K_s versus water content curve for MAD = 0.4.

ambiguities in their definitions.

The FAO Penman-Monteith equation requires altitude above sea level, latitude, air-temperature, humidity, radiation, and wind speed data for daily, weekly, ten-day, or monthly periods for calculations of ET_o. For daily estimation, the FAO Penman-Monteith equation is given as:

$$ET_o = \frac{0.408\ \Delta\ (R_n - G) + g\ \frac{900}{T + 273} U_2 (e_s - e_a)}{\Delta + g\ (1 + 0.34\ U_2)} \qquad (4.6)$$

where: R_n = net radiation at the crop surface (MJ m^{-2} d^{-1}),

G = soil heat flux density (MJ m^{-2} d^{-1}),

T = air temperature at 2-m height (°C),

u_2 = wind speed at 2-m height (m s^{-1}),

e_s = saturation vapor pressure (kPa),

e_a = actual vapor pressure (kPa),

$e_s - e_a$ = saturation vapour pressure deficit (kPa),

Δ = slope vapor pressure curve (kPa °C^{-1}),

g = psychrometric constant (kPa °C^{-1}), and

900 = a coefficient for the reference crop

Procedures for estimating missing climatic data used in the FAO Penman-Monteith equation are provided (Allen *et al.*, 1998). When solar radiation data, relative humidity data and/or wind speed data are missing, they can be estimated using the procedures presented in FAO manual 56 (Allen *et al.*, 1998) and compiled in Appendix A as parts of a VB code. As an alternative, daily ET_o can be estimated using the Hargreaves equation:

$$ET_o = 0.0023(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5} R_a \quad (4.7)$$

where: T_{max}, T_{min}, and T_{mean} are maximum, minimum, and mean air temperature, °C

R_a = extraterrestrial radiation, mm d^{-1}

It is recommended that the above equation be verified in each new region where it is used by comparing the values with estimates from the FAO Penman-Monteith equation wherever the required climatic data is available. The climatic data used in the irrigation schedule in this study to estimate ET_o, and effective precipitation were downloaded from National Climate Data Center web page (http://lwf.ncdc.noaa.gov/oa/climate/stationlocator.html).

To study the impact of the year-to-year weather variability on the irrigation schedule, at least thirty years of data was preferred. The station closest to the site (69 km away) that provided the desired climatic data with that length of record was Knoxville McGhee Tyson Airport at Knoxville, TN, United States. The station is located 293.2 meters (961.7 ft) above sea level, 35°49' N, and 83°59' W. The climatic parameters used and the data available for each month are given in table 4.4.

Table 4.4. Inventory of monthly weather parameters from 1971 to 2001 for Knoxville, TN.

Label	Description	# Years (months) Missing	Total month available
TMAX	Daily maximum temperature	-	372
TMIN	Daily minimum temperature	-	372
TSUN	Daily total sunshine	96(5)/99(3)/00-01	340
PRCP	Daily precipitation	-	372
MXRH	Maximum relative humidity	71-83/97(3)	224
MNRH	Minimum relative humidity	71-83/97(3)	224
AWND	Average daily wind speed	71-83	216

The irrigation schedule was run with the evapotranspiration and precipitation data for the 31 years of data available from 1971 to 2001. To save computation time, it was assumed that the same crop was used and that the days of planting were the same for all years.

For each year, two parallel irrigation schedules were available. In the first irrigation schedule, the calculated AWHC from the merging algorithm was used to estimate the irrigation amounts and date. The first irrigation was scheduled such that soil water content was optimum and no stress occurred. The irrigation amounts corresponded to the net amount required to replenish the soil water to the field capacity of the AWHC. The second irrigation schedule used the actual AWHC of each area in the field. The same evapotranspiration and effective precipitation set used for the first schedule was used for the second irrigation schedule. The prescribed irrigation schedule of the first model was used as the irrigation management strategy for the second model. The second irrigation schedule model computed the water balance, soil moisture depletion, water applied, and actual evapotranspiration of the crop. The ET_a for a set of evapotranspiration and precipitation data changed depending on the irrigation management layout considered. The ET_a values were then used to estimate crop yield.

Estimating yield

Yield estimation was based on a simple water stress equation that relates yield potential with relative evapotranspiration. The relationship was first introduced by De Wit (1958) with transpiration for the season, and later enhanced by Hanks (1974), who added growth stages. Since the relation between transpiration and evapotranspiration is a

close one, and considering that evapotranspiration is more easily measured or estimated by a variety of models, the relation can be expressed as (Doorenbos and Kassam, 1979):

$$Y_a = Y_m - Y_m(K_y\,[(1 - (ET_a / ET_m)]) \qquad (4.8)$$

where: Y_a = actual yield at some irrigation level

Y_m = maximum yield, under all optimum conditions

K_y = yield response factor

ET_a = actual evapotranspiration

ET_m = maximum evapotranspiration

Knowing the expected maximum yield, and calculating the evapotranspiration relationship from the irrigation scheduling, the actual yield can be obtained. This relation has been used for deficit irrigation (Martin *et al.*, 1984; Timlin *et al.*, 2001). It can also be applied to site-specific irrigation analysis. Water stress (or deficit irrigation) occurs in the low AWHC areas of non-uniform fields when irrigation is applied uniformly. Equation 4.8 is based on the assumption that when full crop water requirements are met by the available water supply, the ET_a is equal to the ET_m given by the climatic demand. For site-specific irrigation, when the evapotranspiration demand is fully met, maximum crop yield is expected if other inputs do not limit the yield. However, when uniform irrigation is applied to different management units (non-uniform field), parts of the field will not receive the proper amounts of crop water because the water balance is not the same for the whole field. This condition of non-optimum irrigation causes water stress and prevents the yield from reaching the maximum. For those parts of the field, the water application will not match the crop water requirement balance, and the ET_a will be reduced compared with the ET_m because of the limited water available in the soil. The

level of crop water stress is associated with the crop stress factor (ET_a/ ET_m) and the crop sensitivity to the yield response factor (K_y). To account for the varying susceptibility of the crop due to the growth stage, equation 4.8 can be modified to:

$$[(Y_m - Y_a)/ Y_m] = 1 - Y_{a1}/Y_{m1} \times Y_{a2}/Y_{m2} \times .. \times Y_{as}/Y_{ms} \quad (4.9)$$

where: Y_{a1}/Y_{m1} = ratio of actual to maximum yield for 1st stage of growth

Y_{a2}/Y_{m2} = ratio of actual to maximum yield for 2nd stage of growth

Y_{as}/Y_{ms} = ratio of actual to maximum yield for "s" stage of the growth

For each stage "s" a K_y value was assigned and the computation proceeded as in equation 4.8. The K_y values for tomatoes are given in table 4.3. To ensure that the yield reduction reaches values close to 1 for maximum evapotranspiration reduction, the K_y is increased to 1.7 if the evapotranspiration reduction is above 0.6 (60%) and the K_y value is smaller than one.

Doorenbos and Kassam (1979) provided some guidelines for finding the maximum yield. First, they presented a general climatic model to find the crop maximum values, or secondly suggested the use of reported values as the maximum yield. A further study in this area suggested a distinction between these two approaches. Evans and Fischer (1999) suggested the use of the term potential yield for comparisons between different crops and different environments, as well as yield that could be reached by a crop in a given environment. For example, yield simulation models with plausible physiological and agronomic assumptions are available to find plausible future limits to crop yields. Evans and Fischer (1999) suggested a yield potential term for estimating measured comparisons of cultivars when grown in environments in which the cultivars adapted and with all production factors at optimum levels. In this case, the yield potential

for tomatoes or the maximum yield with no limiting factors for the environmental conditions of the selected site can be obtained from past cultivar comparison experiments, and from observed maximum values obtained in production fields.

In a yield performance study of 10 tomato cultivars evaluated at The University of Tennessee, Knoxville Experiment Station (Coffey, 2001), the highest observed yield was 3,777 boxes per hectare (377.75 cwt/A). However, in a commercial tomato field with smaller spacing between plants, higher yields are obtained. Mullins et al. (2001) conducted an experiment at the Middle Tennessee Experiment Station at Spring Hill, TN to evaluate performance of 17 tomato cultivars. The 'Florida 91' cultivar yielded 6,220 boxes per hectare (622 cwt/A) of fruit size of No. 1 and 2 grades combined. The tomato budget used as a model for this study reported a maximum yield of 4,537 boxes per hectare (453.75 cwt/A) that can be obtained in typical commercial production in Tennessee. To be consistent with the tomato budget, the maximum yield of 4,537 boxes per hectare was used for the value of Y_m (Appendix B). Each box weighted 11.34 kg (25 lb).

Estimating net return

An important decision criterion was the net return or profit for a field, defined as the total revenue minus total cost. To identify the total cost, a crop budget for tomatoes was used. The crop budget was developed by the Tennessee Experimental Agricultural Extension Service (www.utextension.utk.edu/hbin/TomatoBudget.pdf). The tomato budget was modified to suit the particular case of site-specific irrigation management (Appendix B).

Gross income

The gross income was estimated as the actual yield multiplied by the cropped area multiplied by the price of the product. The actual yield was estimated over the 1971 to 2001 period using the irrigation schedule and the crop stress function described previously. The expected price used was the farm price reported for each year between 1971 and 2001 (Tennessee Crop Reporting Service, 1985; TN Department of Agriculture, 2002). The price received by farmers index of fresh vegetables (U.S. Department of Agriculture, 2002) was used to convert nominal prices to prices stated in 2001 dollars. Because the base year for the index was changed from 1977 to 1992 in 1994, the methodology to calculated the prices was done using a splicing index time series (Lapin, 1973). The year-to-year observed prices, the price index, and the price values (for 2001) used on the analysis are reported in table 4.2. Year-to-year price was used in view of the fact that yields and price fluctuations are probably correlated.

Costs

The variable expenses and fixed costs were modified from the original budget as shown in tables 4.5 and 4.6. Other costs were calculated separately because the costs were dependent on the site-specific layout. These site-specific costs were the labor for harvest, labor for the irrigation set-up, the fixed costs for extra headlines, the fuel used for pumping water, and extra control units.

The annual crop costs were $8,712/ha ($3,484.87/A) – these were the fixed and variable costs without irrigation costs. The irrigation cost per area independent of the field layout was $669/ha ($267.93/A); the details of the irrigation cost are given in table

Table 4.5. Estimated variable and fixed irrigation cost per hectare.

Variable Expenses/Irrigation		Quantity	Unit	Price/unit	Total
Pkgs, Supplies	Drip Tape	2.5	rolls	130	325.00
Labor	Irrigation Maintenance	27	h	8	219.36
Irrigation	Repairs & maintenance	1	ha	16.87	16.87
Interest	Operating Capital (6 mo.)	561.23	$	10.00%	56.12
Total Variable Expenses					617.36
Fixed Irrigation Cost					
	Irrigation (16) Depreciation	1	ha	54.19	54.19
	Interest	1	ha	28.12	28.12
Total Fixed Expenses					82.31
Total Annual Costs Irrigation					699.66

Table 4.6. Estimated costs of the irrigation system per hectare.

Irrigation system		$/ha					
		Price	Life	Repairs	Depreciation	Interest	Total
Pump	25 hp	3,200	9	5.93	21.98	9.89	37.80
Sand Filters		4,900	20	9.09	15.14	15.14	39.37
Connections		300	3	0.56	6.18	0.93	7.66
Blue Lay Flat – 6 in x 300 ft		400	3	0.74	8.24	1.24	10.22
Fert. Injector		300	7	0.56	2.65	0.93	4.13
Total		9,100		16.87	54.19	28.12	99.18

4.5. The non site-specific costs were then combined in a term called Cost of Crop per area (CC), which was $9,382/ha ($3752.80/A) – the complete costs are found at Appendix B.

The site-specific costs that were affected by the field management layout are discussed below. The first is the cost of harvest labor.

Harvest cost

The harvest cost was corrected for the variable yield, because the labor for harvest in tomatoes is directly related to yield. These costs were dependent on the irrigation management layout, because depending on the layout (site-specific or uniform irrigation), the yield was variable due to water stress. The yield was estimated based on the equations discussed previously and the cost of harvest labor was calculated as:

Harvest Labor = labor cost ($0.18/kg) × Yield (kg/ha) × Area (ha) (4.10)

However, to account for the opportunity cost of the money expended with harvest, and to be consistent with the tomato budget, the interest on the capital (assumed as 10%) for the first six months was added to this variable cost. Considering this as an annual cost, the harvest labor cost (HL) is:

HL = Harvest labor + 10% × (Harvest labor/2) (4.11)

Set-up cost

The second labor cost was the variable cost to set up the irrigation system. The set-up cost was considered a site-specific cost because it was dependent on the field layout management. More complex irrigation systems require extra time for installation. For each extra management unit, the installation of a control unit package (board, sensors, and valves) requires approximately two hours of work.

The labor cost of the original budget was maintained ($8/h). For the 1.67 h/ha (0.67 h/A) required to install the equipment, (26.8 h for the 16.18 ha), two extra hours were added for each additional layout, and some extra time was also required for the additional pipes and connections to make the system work, bringing the value to 1.78 h/ha. The incremental times required for labor from the uniform management to the completely site-specific were plotted related to the number of management units considered in each layout (figure 4.3), which shows a positive linear relation between the number of management units and the extra labor hours. This number presented in figure 4.3 can be applied only to this field, because the extra time besides the control unit installation time considered the complexity of the headlines installation. In the spreadsheet a linear regression of the set up labor with number of management units was used, but it may have been better to use the actual value points. In this case, set up hours per area was computed as:

$$\text{Set-up Hours per area} = 1.78 + 1.78\ (\#\ MU \times 0.0595) \quad (4.12)$$

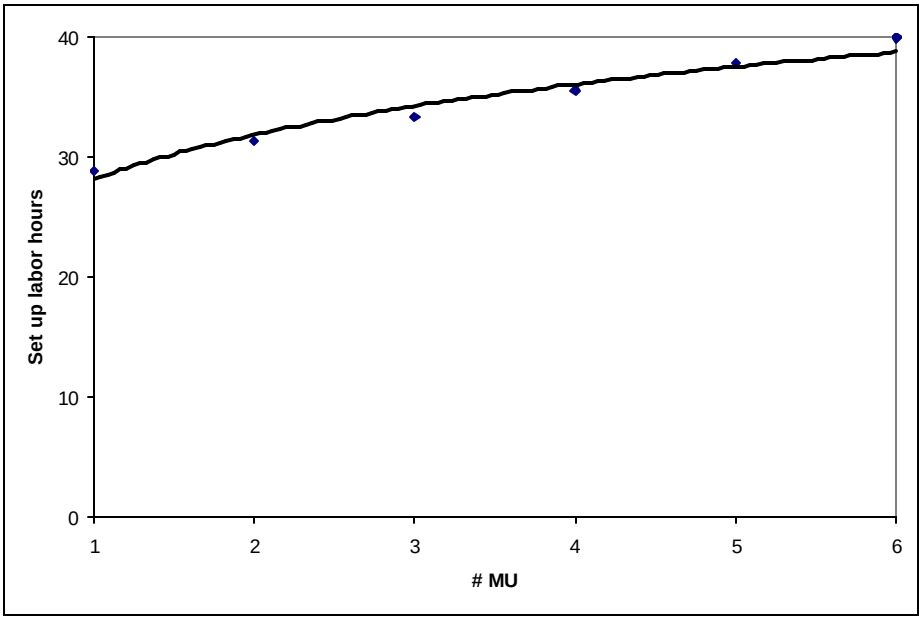
$$\text{Set-up Labor} = \text{Set-up Hours per area (hr/ha)} \times \text{Area (ha)} \times \$8/h \quad (4.13)$$

To account for the opportunity costs and to be consistent with the tomato budget, the interest cost of the variable capital for the first six months was computed, and the labor cost for set-up (SL) was:

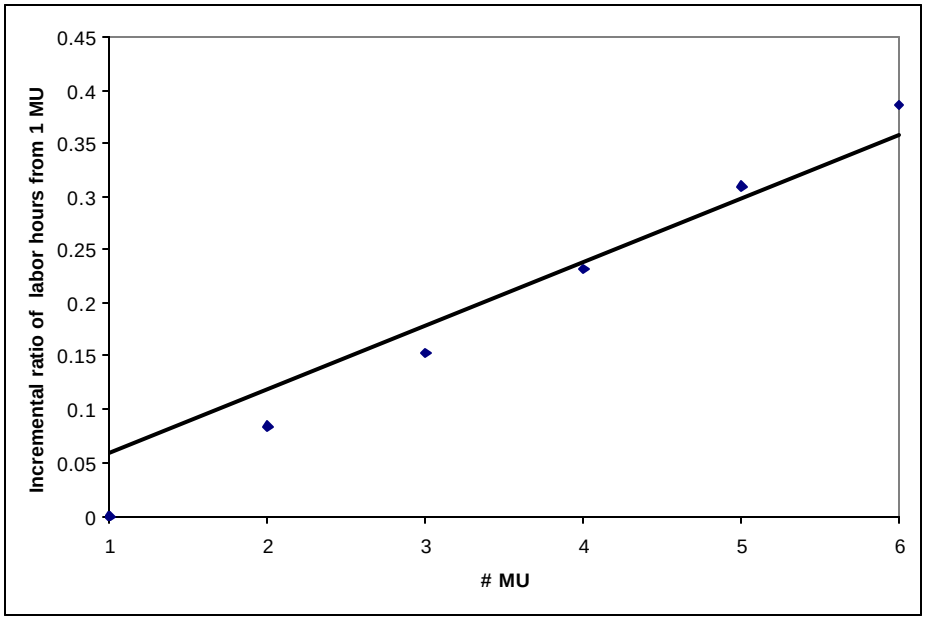
$$SL = \text{Set-up Labor} + 10\% \times (\text{Set-up Labor}/2) \quad (4.14)$$

Headline cost

This cost was the cost of headlines that carry water to each sub-area in the field. As the number of management units increases, dependent on the field layout management, more equipment is required for the irrigation system. An estimate of the



a)



b)

Figure 4.3. Relation between set up labor hours and number of management units (MUs): a) Set up labor hours and number of management units, b) Incremental hours ratio from one management unit.

extra material was made for the different layout. Meters of headline in the field versus the number of management units are shown in figure 4.4, these numbers are specific for this field.

To estimate headlines, first the direction of main lines and drip lines were design for the field. The design observed the direction of row crop and the source of water in relation to the field. Once the drip lines, and main lines direction was selected, the headlines were drawn perpendicular to the drip lines and not allowing the drip lines to exceed 120m (to reduce friction loss). The irrigation system was first designed for the uniform management layout; as a new management unit was treated individually, an extra headline was required to supply the drip lines that apply water for that management unit. In this way, the original length required for the uniform management irrigation was increased as more management units required individual treatment.

$$\text{Length of Headlines} = 137.13 \times (\#MU) + 845.12 \quad (4.15)$$

$$\text{Headline Total Cost} = \text{Length Headlines} \times \$4.17/m \quad (4.16)$$

The linear relation in equation 4.15 was used to facilitate the computation in the spreadsheet, the use of the actual values of headline length is advised, and the equation is particular to the field studied. The headlines are a fixed cost and the total cost should be considered over the life of the headline life span. Other fixed costs in the tomato budget were broken down into repairs, depreciation, and interest costs:

$$\text{Repairs} = \text{Headline Total Cost} \times 3\% \quad (4.17)$$

$$\text{Depreciation} = \text{Headline Total Cost} / \text{life span} \quad (4.18)$$

$$\text{Interest} = (\text{Headline Total Cost}/2) \times 10\% \quad (4.19)$$

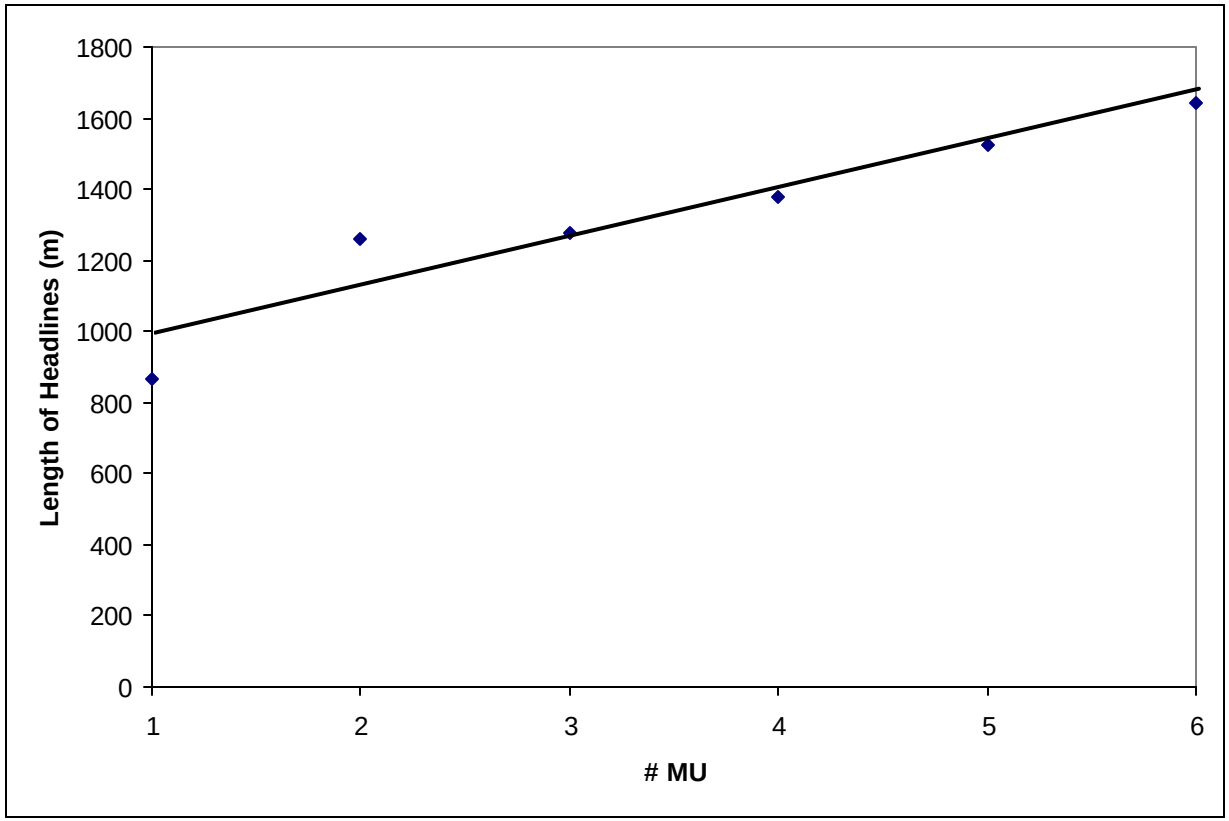


Figure 4.4. Length of headlines related versus number of management units (MUs).

Table 4.7. Annual fuel consumption index.

Fuel or power source	Efficiency	Factor of power per unit of fuel
Electric	80	797.9 W per kW-Hour
Gasoline	20	1.92 kW per liter
Diesel	26	2.82 kW per liter
Propane/Butane	21	1.53 kW per liter
Natural Gas	21	2.15 kW per cubic meter

The life span considered for the depreciation calculation was three years. The final annual cost of the headlines (CH) was:

CH = Repairs + Depreciation + Interest (4.20)

Fuel cost

Another site-specific cost was the fuel used for irrigation. The variable cost of the fuel was related to the size of the pump, hours of operation, and the amount of water pumped. The variable cost of the fuel was calculated as:

Fuel Cost = [Power of pump × Operation Hours × CF]/Factor (4.21)

where: Fuel cost = the cost of the fuel in $

Power of pump = the horsepower required to operate the pump, kW

CF = the cost of fuel, $/liter

Factor = the conversion factor of power per unit of fuel, kW-h/liter

Operation Hours = total time in hours that the pump is operating, h

The conversion factors for different power sources (Buchanan and Cross, 2003) are given in table 4.7. Operation hours were computed as:

Operation Hours = [water applied × MUarea]/pump flow rate (4.22)

where: water applied = season irrigation depth, mm

MUarea = area of management unit, m^2

pump flow rate = the flow rate of selected pump, liter/h

The lubricant cost was considered as a fraction of the fuel cost (Fuel Cost × 0.15); the combined Variable Fuel and Lubricant costs (VFL) was:

$$VFL = \text{Fuel Cost} + \text{Lubricant} = \text{Fuel Cost} \times 1.15 \quad (4.23)$$

The Fuel and Lubricants (VFL) cost, was given as:

$$VFL = VFL + 10\% \times (VFL/2) \quad (4.24)$$

Control unit cost

The control units are a decentralized microcontroller circuit that monitors the soil moisture content and applies water by opening valves when the water content reached defined level. The cost of the control units used to monitor and control the irrigation application was a fixed cost that was transformed into an annual cost. This cost was dependent on the number of units in the field. The annual cost of one control unit was $72, as detailed in table 4.8. Depending on the layout, for each additional management unit in the field, one extra control unit was required, so the cost of control units (CCU) was $72 × #MU.

Table 4.8. Annual cost of control unit.

Site-Specific Control Unit	Total cost[a]:		Annual cost, $/unit			
	Price	Life (yrs)	Repairs	Depreciation	Interest	Total
Solenoid valve	37.50	7	1.13	5.36	1.88	8.36
Soil water sensors	86.99	3	2.61	29.00	4.35	35.96
Solar panel	77.35	20	2.32	3.87	3.87	10.06
Microcontroller circuit	90.66	20	2.72	4.53	4.53	11.79
Battery	14.5	3	0.44	4.83	0.73	5.99
Total	307		9.21	47.59	15.35	72

[a]Source: Miranda (2003)

Survey cost

Finally, the cost of the intensive survey to acquire the soil spatial information at the scale that this field was investigated is estimated at approximately $25/ha ($10/A) (Denton, 2003). For uniform irrigation, i.e., one management unit, there was no cost for the extra survey, because that information was not required. For site-specific irrigation the survey cost was $401 and was independent of the layout. Because it was a one-time investment, the cost of the extra survey could be treated in one of two ways. First, it could be treated as a sunk cost and ignored when costing out strategies. Second, it could be treated as a depreciable asset, and amortized over the assumed useful life of the equipment using capital recovery. This would be a very small amount, if amortized over 31 years. Either way, this cost is minimal when considered over the years. In this case, the survey cost was treated as a sunk cost, and ignored in calculating net revenues for the alternative strategies. All the costs and the factors that affect the total cost are summarized in table 4.9.

Table 4.9. Summary of the fixed and variable costs used in the analysis.

Legend	Description	Component factors
CC	Cost of Crop	Crop, area
HL	Harvest Cost	Labor ($/kg), yield, area
SL	Set-up Labor Cost	Labor ($/h), #MU
CH	Headline Cost	#MU, Price of headline
VFL	Fuel and Lubricant Cost	Amount of water pumped, Pump size, Price of fuel, Type of pump
CCU	Cost of Control Unit	#MU, Price of equipment
TC	Total Costs	CC, HL, SL, VHL, CH, and CCU

Statistical analysis

Site-specific results

A statistical analysis was performed to evaluate the results from the various irrigation management layouts. A program was written in SAS® to verify the statistically significant differences among the six layouts over the years of analysis. Because of the great variability from year-to-year, a randomized block design with years as block was selected. The code used the ***rbd*** macro developed by Saxton (2001). This macro was used to compare the differences of the tomato production, water loss, gross return, cost of fuel, and cost of harvest among layouts. Besides computing the statistical differences among the layouts, the macro also performed additional statistical tests, such as equivalence of the standard deviations and a test of normality.

Net return results

A statistical analysis was performed to evaluate the net return results from the various irrigation management layouts. The SAS® PROC FREQ was used to test the ranking scores of the different layouts over the years. The unequal variability of the model among the different irrigation management layouts required a Friedman's chi-square test. This test was used to rank the different layouts from 1 to 6 starting with low values; values that were not significantly different received the same scores.

CHAPTER 5

RESULTS AND ANALYSIS

Verification of the site-specific irrigation schedule

Verification of the site-specific irrigation schedule (SSIS) was performed to check the integrity of the mathematical manipulations, the logic of the programming, and to verify that the units and conversions were in the right format. CROPWAT (version 4.2) was selected as the software to be compared with the SSIS. Most of the equations in the water balance model used in the SSIS were similar to the ones used in CROPWAT (Smith, 1992). However, the CROPWAT model was not selected as the primary irrigation scheduler for this analysis because of the limitations on the input parameters. For instance, CROPWAT only accepts monthly value of inputs, it uses a distribution method to obtain daily values from the monthly values, and this distribution method was a source of uncertainty to be avoided. Even more questionable in CROPWAT is the method used to obtain daily values of rainfall. Monthly total rainfall values are distributed into daily values. The daily rainfall values are then added based on a fixed number of days selected by the user; rainfall is assumed to occur at the end of this fixed interval of days. Because of this limitation in the daily rainfall estimator, the verification was done with the assumption of no rain.

Verification of the output of both models when given the same input was performed. The average monthly evapotranspiration (ET) for Knoxville was used as an input into CROPWAT. The model distributed the ET values into daily values by fitting a curve with the monthly values. The disaggregated daily values of ET from CROPWAT were used as the input for the SSIS, because the actual values of daily ET could not be

used in CROPWAT. Daily soil moisture content values predicted by the SSIS and CROPWAT for the Toccoa soil series are shown in figure 5.1. Irrigation application was performed when the soil moisture depletion (SMD) equaled the readily available moisture (RAM). The net applied irrigation amount was equivalent to the amount of water required to bring the soil water content to field capacity. The readily available moisture increased over the growing season as a function of root depth (R_d) development and the management allowable depletion (MAD) coefficients. The smallest difference in SMD between SSIS and CROPWAT was at the beginning of the growing season due to differences in the interpolation of the MAD coefficients. After MAD stabilized at the end of the development stage, the differences in SMD disappeared.

The soil moisture content estimated by SSIS and CROPWAT for the Buncombe soil series is shown in figure 5.2. The irrigation of this soil unit illustrates the second irrigation schedule described in Chapter 4. In this case, the irrigation schedule was performed with the prescription (dates and amounts) of the previous run. The Buncombe (TAM = 50 mm/m) soil series was irrigated with the schedule defined for the Toccoa (TAM = 120 mm/m) soil series. As can be seen in figure 5.2, the soil moisture depletion went beyond the RAM, causing water stress to the crop. The yield reduction estimated by the SSIS was 49.4%, compared with 49.3% estimated by CROPWAT. Again, the small difference in SMD predicted by SSIS and CROPWAT was due to the MAD interpolation in the early stages of the development.

The fitting of the two SMD predictions from the two models is presented around the 1:1 line in figure 5.3. Regression analysis resulted in a high coefficient of

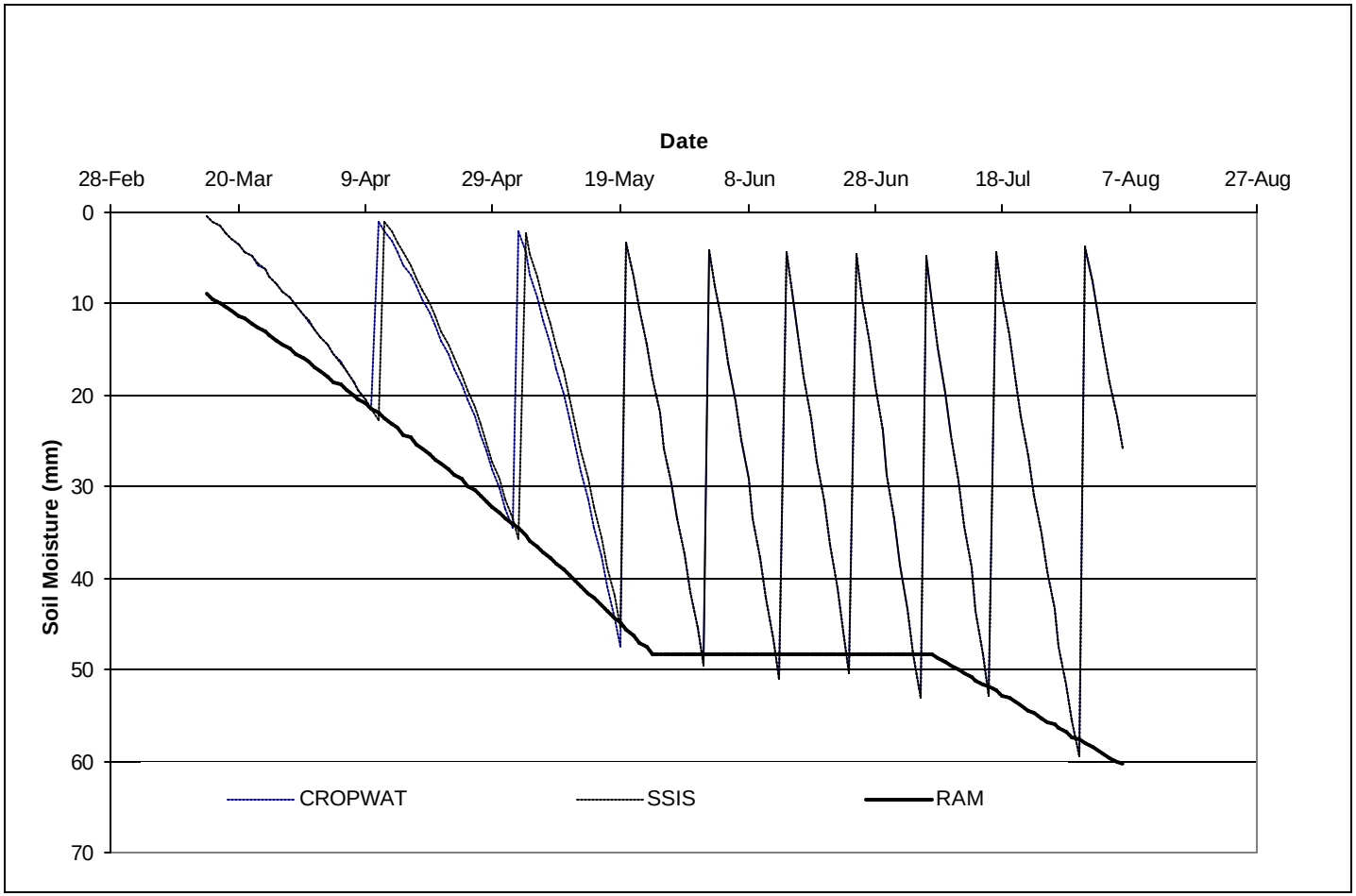


Figure 5.1. Soil moisture content simulated by CROPWAT and SSIS for Toccoa soil series.

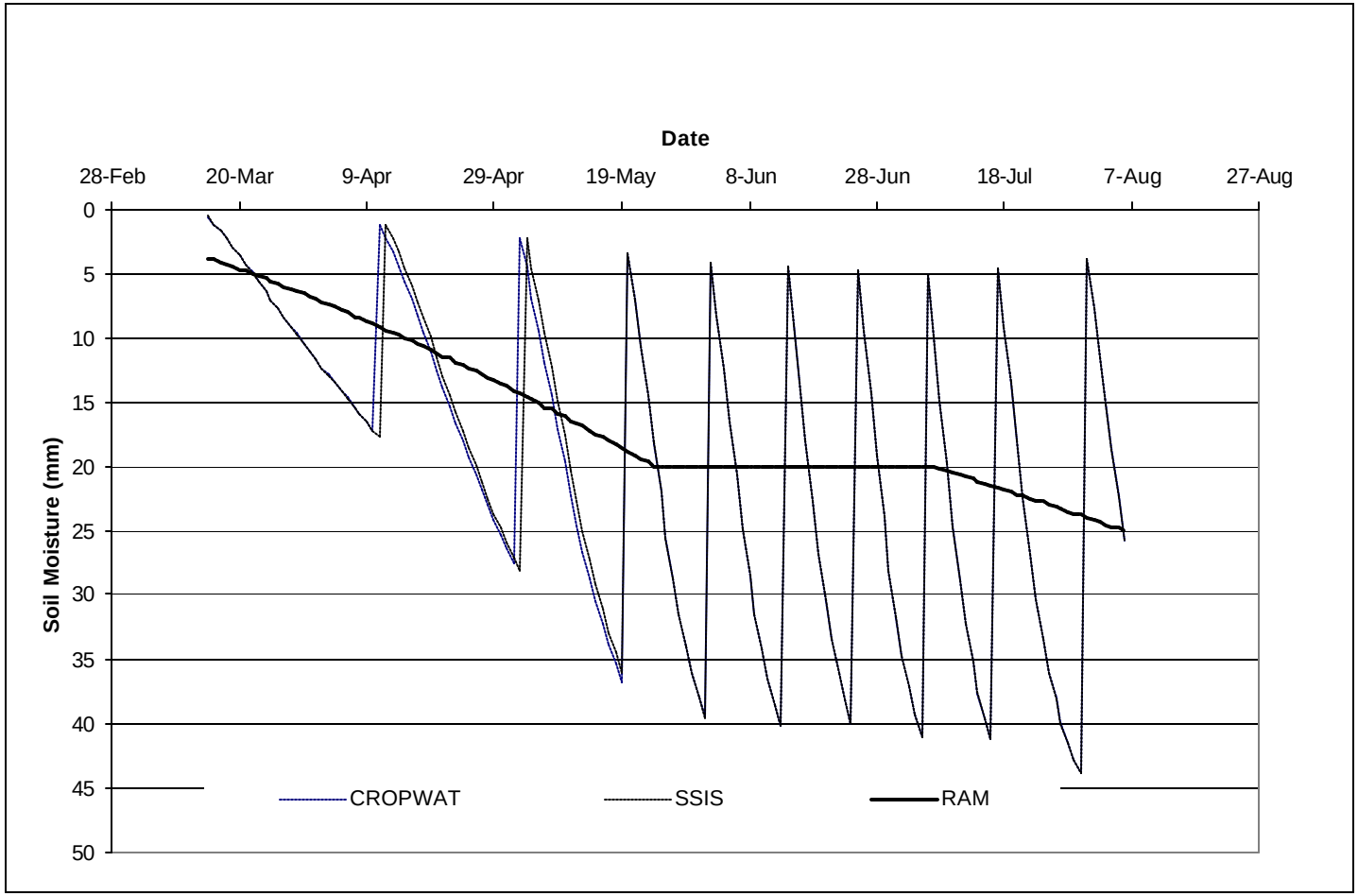


Figure 5.2. Soil moisture content simulated by CROPWAT and SSIS for the Buncombe soil series, using the irrigation control from the Toccoa soil.

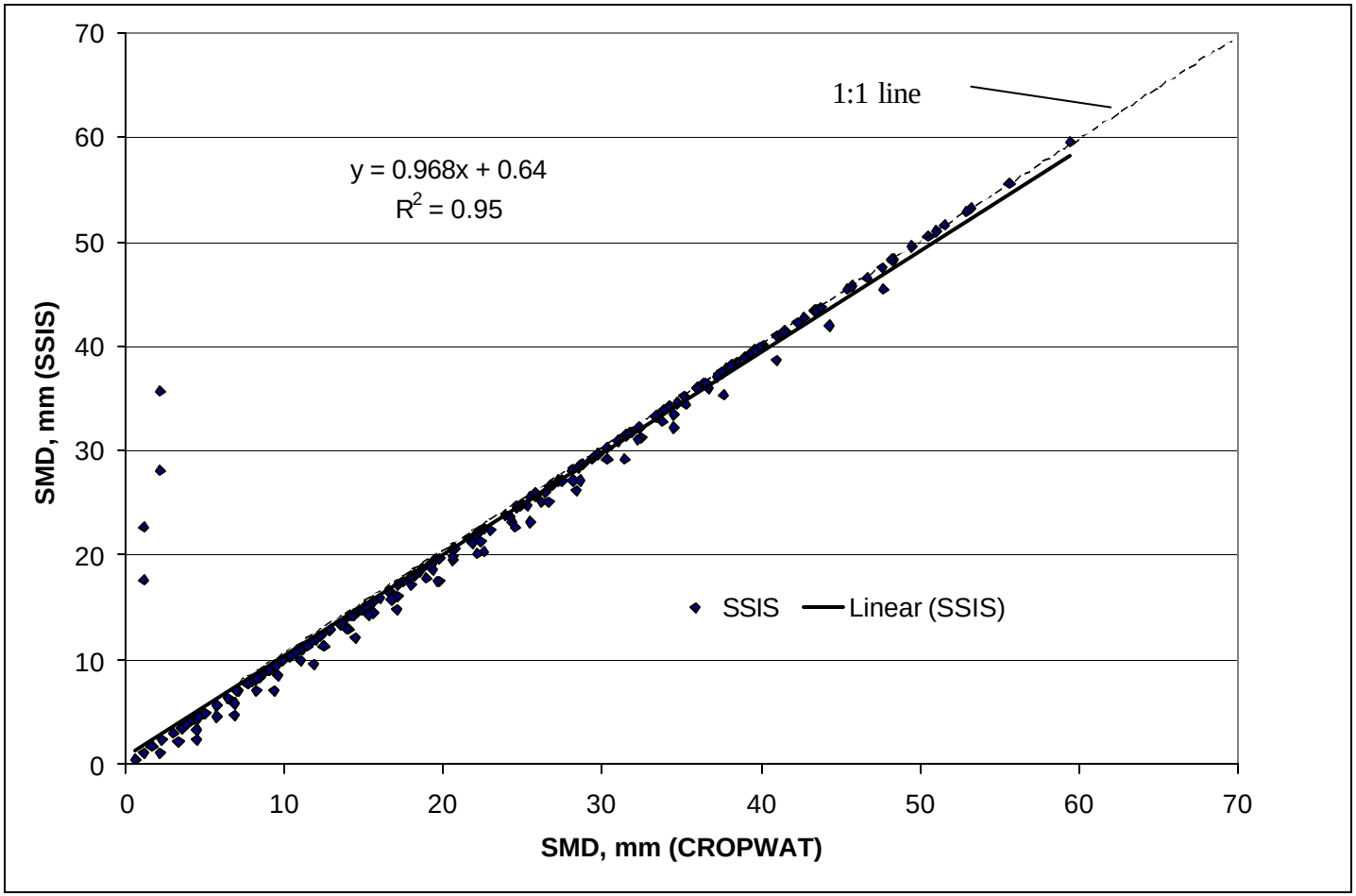


Figure 5.3. SSIS and CROPWAT curve fitting distribution for both soil series.

determination (R^2 = 0.95), even though some points were clearly outliers. These outlying points were caused by the difference of one day in the irrigation schedule. In the SSIS, the irrigation was performed on the next day, since the RAM was slightly higher than the values in CROPWAT due to the MAD values. The higher RAM allowed the moisture of the soil to be depleted further, reaching the RAM threshold on the next day. Therefore, the outlying points in figure 5.3 represent equivalent values, shifted for one day around the irrigation date, at the early stage of the crop growth. For the remainder of the crop growth, there was no difference in SMD estimation.

Validation of the yield estimation module

Yields simulated using the yield reduction model (Equation 4.9) were validated. The validation, also called accuracy assessment or error analysis, consisted of comparing simulated (model) results to real system data. In this case, soybean yield data from 1998 were used for the analysis. The soybeans were not irrigated. The yield was collected with grain yield monitors equipped with a DGPS receiver. The data were recorded on PCMCIA (Personal Computer Memory Card International Associations) memory cards and were downloaded into a personal computer as text files. These text files included spatially oriented yield data logged every 1 seconds during soybean harvest. Latitude, longitude, flow rate (lb/s), yield (bu/A), and percent moisture data were recorded for every position.

Filtering the data was necessary to remove bias readings that occurred when the combine was rapidly accelerating or decelerating. Because the time interval between data points was constant, distance as a substitute for speed was used to filter the yield data. The distance data field represented the distance traveled by the combine from the

previous yield data position. The distance used for filtering was 1.22 m (48 in); values taken less than 1.22 m apart (i. e., 4.4 km/h) were excluded (Appendix C).

The soybean yield values were averaged for each soil-mapping unit, based on the points that fell within the soil unit. The values were originally reported in bu/A, a conversion factor of 67 (62 lb/bu) was used to obtain kg/ha (Appendix B). The soil map with the average observed data for each soil-mapping unit is shown in figure 5.4. Management unit 6, one of the Congaree soil units, had the highest average yield (3,140 kg/ha) for this year of analysis. Management unit 3, the State soil unit, and the other Congaree soil unit, management unit 2, also had high yield values (3,097 kg/ha and 3,032 kg/ha) for this year. Management unit 4, soil unit Buncombe, had the lowest yield (1,608 kg/ha), representing only 51.2% of the maximum average yield in unit 6 (3,140 kg/ha).

Yield reduction is a complex parameter and may be a function of a variety of factors other than water stress. However, it was important to evaluate how well the yield reduction function estimated the yield for this particular area. For this validation, the site-specific irrigation schedule was modified; instead of computing water application, the water balance was used to estimate soil moisture and evapotranspiration. Evapotranspiration reduction was estimated based on the water stress, caused by the inadequate water content in the soil (drop in soil moisture). From evapotranspiration reduction, yield reduction was estimated using equation 4.9. The coefficients used were standard soybean coefficients (Smith, 1992; Allen *et al.*, 1998). Since soybean planting in this county generally occurs some time in May, May 15, 1998 was used as the planting date.

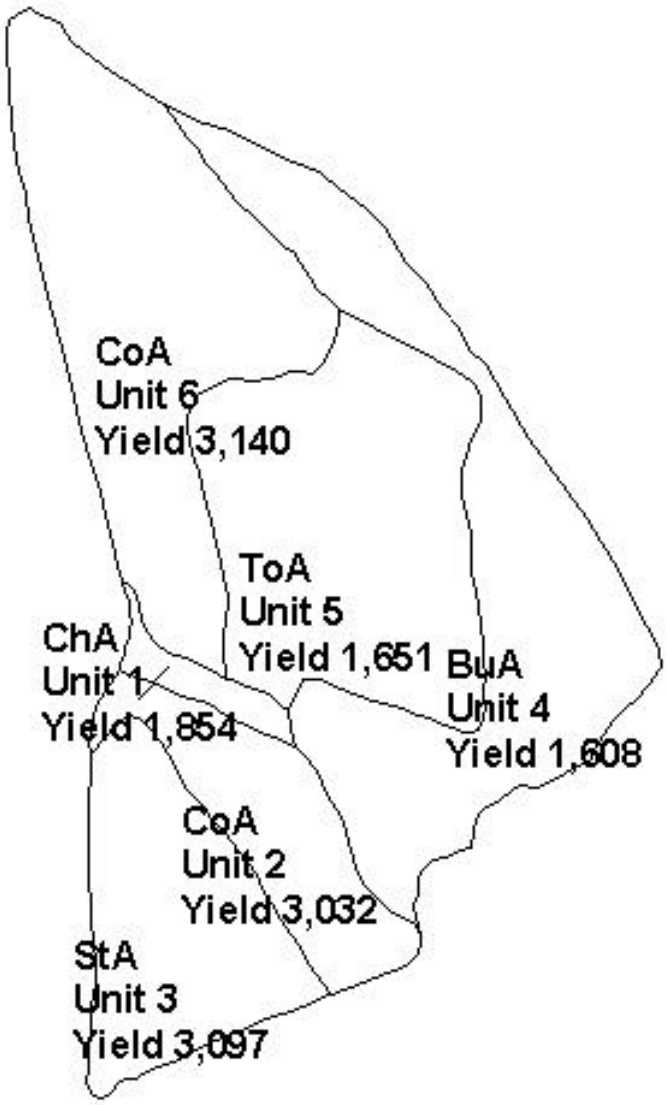


Figure 5.4. Averaged soybean yield for each soil-mapping unit (1998), soil unit abbreviation followed by soil unit number, and average yield (kg/ha).

The 1998 year had one of the largest cumulative evapotranspirations during the 31-yr period of analysis (1971-2001). In fact, the cumulative ET was the third highest of all years measured, with only 1987 and 1988 having higher ET values. The cumulative precipitation in that year (274.2 mm) was close to the average annual value (204.14 mm). The difference between cumulative evapotranspiration and precipitation over the growing period of the crop for 1998 was among the top 30% highest values. Values of predicted yield, cumulative evapotranspiration, and precipitation over the growing period of the crop are given in Appendix C.

Equation 4.9 only gives yield reduction, and a maximum yield value had to be assumed for the area. The observed average soybean yield in Cocke County in 1998 was 1,876 kg/ha (28 bu/A) (TN Department of Agriculture, 2002). The maximum yield reading in the study field in that year was 5,561 kg/ha (83 bu/A), with the highest average by soil unit of 3,140 kg/ha (46.86 bu/A). However, Specht *et al.* (1999) reported soybean maximum yield potential of 8,000 kg/ha (119 bu/A), and this last value was used as the maximum limit in the yield estimation.

A bar chart with observed average values by soil-mapping unit and the respective values predicted by the model for the same soil-mapping units is shown in figure 5.5. The predicted values of soybean yield in the study field were within one standard deviation of the average observed values. Overall, the predicted values overestimated the yield reduction, except for sub-areas 1 and 5. In these management units, factors other than the water deficit may have caused the yield to be reduced. The major discrepancy occurred in management unit 1, where the model predicted the minimum yield reduction;

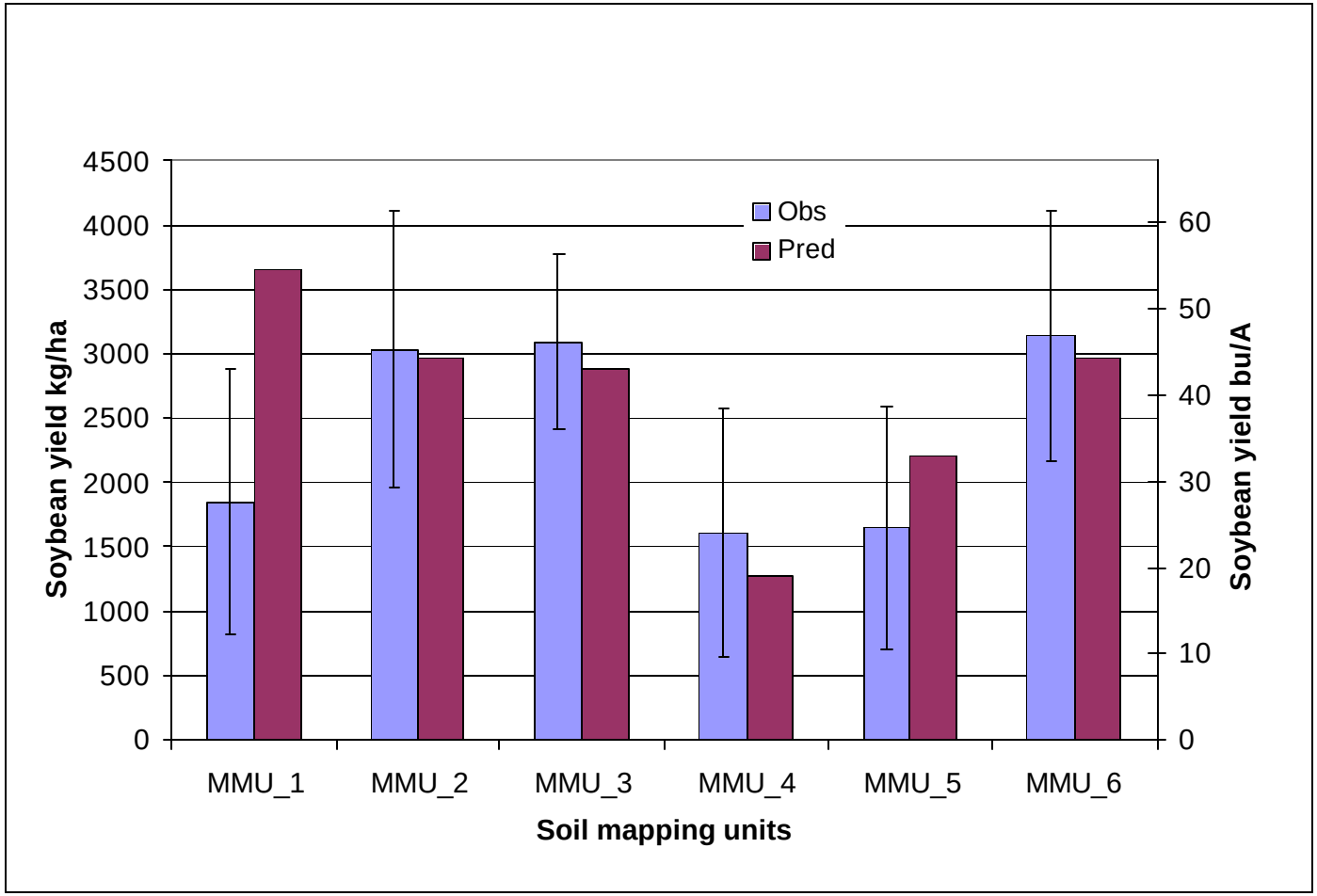


Figure 5.5. Observed average soybean yield compared with estimated yield using the water balance and yield relation functions (data from the study field in Cocke County in 1998 – not irrigated). The error bars represent one standard deviation.

consequently, the maximum predicted yield occurred in management unit 1. The low observed yield in management unit 1 was possibly caused by yield restrictions other than water deficit, perhaps by excess water in the root zone. The Chewacla soil unit in sub-area 1 is considered a poorly drained soil according to the soil series description (Appendix B).

The "goodness-of-fit" between predicted and observed value was low when all sub-areas were considered ($R^2 = 0.24$). The value for management unit 1 clearly represented an outlier for the reasons discussed previously. Therefore, the discrepancies between observed and predicted yield in sub-area 1 were not caused by poor soil water model performance. The observed versus predicted values with the outlier value removed are shown in figure 5.6. In figure 5.6, the 1:1 line shows the best fit possible between observed and predicted values. The curve fitting equation and coefficient of determination are also presented in figure 5.6. The model over-estimated the yield reduction, under-predicting the yield values. The model was able to explain 81 % of the total variability existing in the data, when management unit 1 was removed from the analysis.

The yield estimation equation was not able to represent the observed soybean yield in management unit 1 for 1998. However, if proper drainage or other factors that may have reduced the yield had been provided in this sub-area, maximum yield would have been expected. For this analysis, the effect of water stress was the most important factor, and other restrictions besides water deficit were not considered. Maximum yield was assumed considering that all the factors were at the optimum level, as described in chapters 3 and 4. As a result, management unit one was considered in the final analysis of

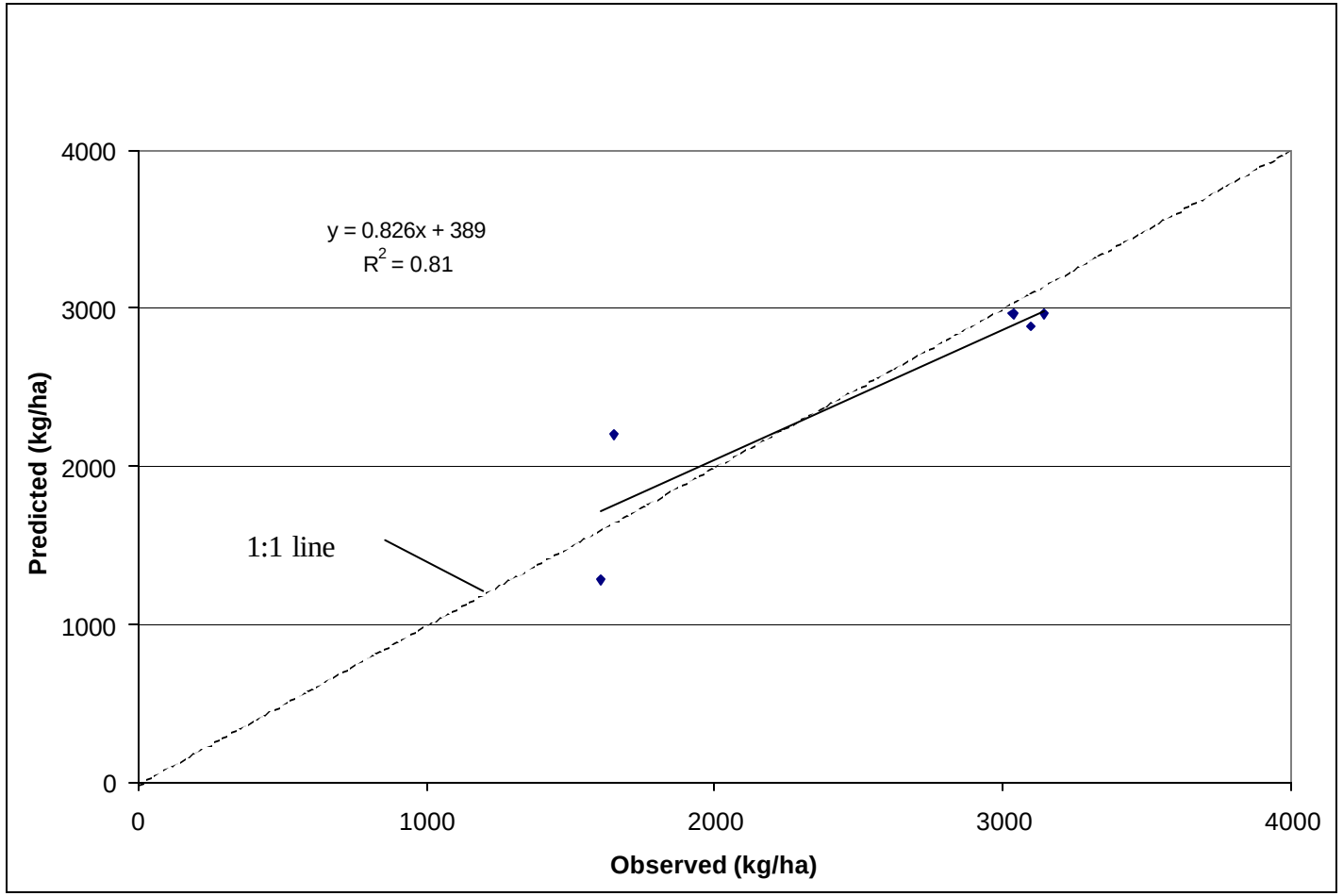


Figure 5.6. Comparison of soybean yield measured and simulated in kg/ha with management units two to six considered, Cocke County field, 1998 data set.

the site-specific irrigation schedule.

SSIS results

After the site-specific irrigation schedule was verified, it was applied to the case study with tomatoes. The irrigation schedule was run for each management unit, considering each layout combination, for a particular year, and for 31 years of data. Tomatoes were assumed to have been planted on March 15 of each year. In this case for the irrigation schedule, the date of plating and all coefficients in table 4.3 were constant over the years; the precipitation and evapotranspiration were variable over the years. Six different management units and six different layouts over 31 years of data resulted in 1,116 data sets. To run the six different layouts for one management unit over the 31 years of weather data required approximately 2.5 min of computer time, on microcomputer with an 800 MHz processor and 256 MB of RAM memory. The data were stored in Excel files and a macro was called to make the computation. The stored output information for each management unit comprised the following:

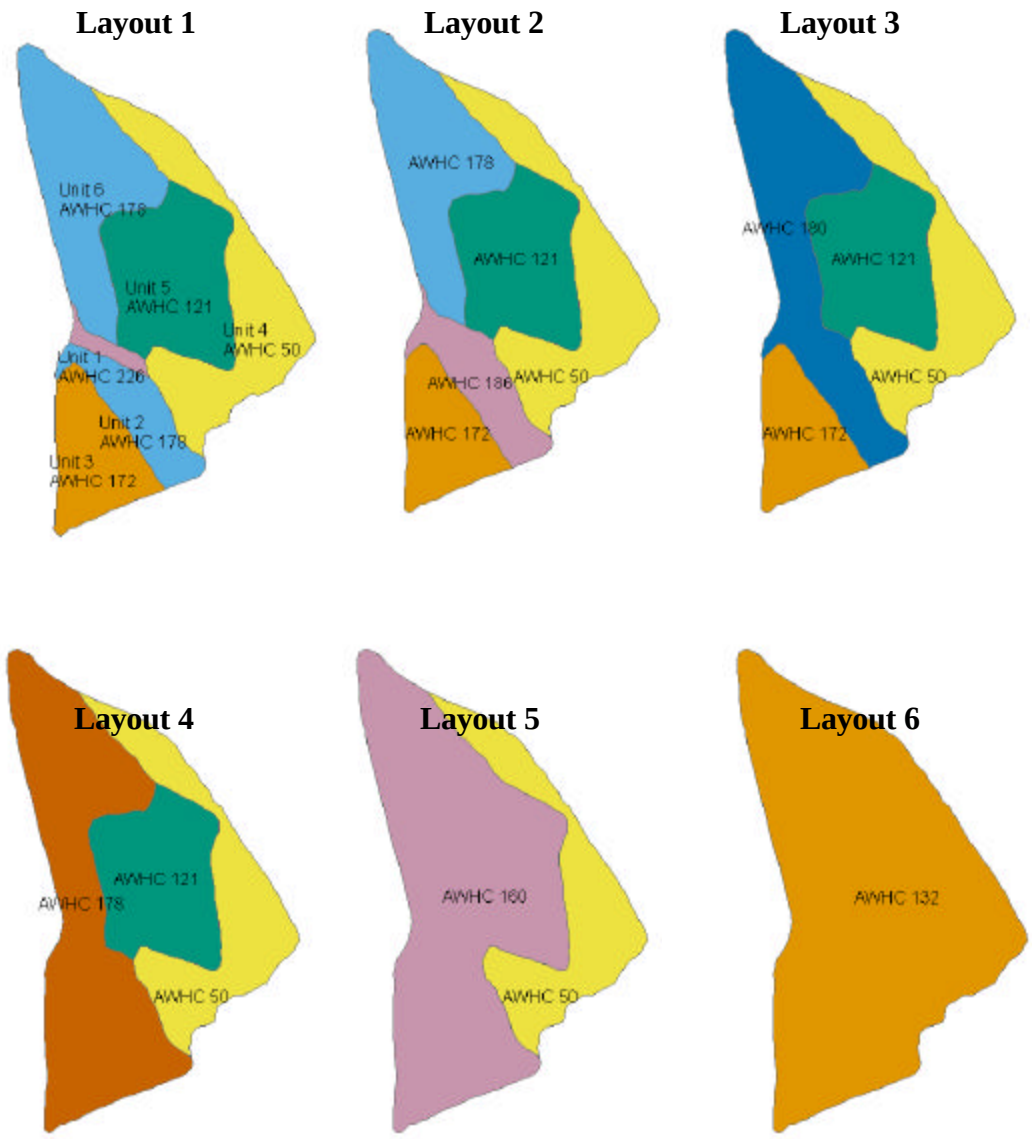
- **Actual AWHC of the management unit**: the original AWHC value from table 4.1
- **The calculated value for the AWHC**: the new averaged AWHC from the merging algorithm, dependent on the layout being considered
- **Net applied irrigation water**: the estimated water applied for each layout depending on the calculated AWHC
- **Water loss**: amount from the net applied irrigation that was lost when the irrigation amount was larger than the SMD value for a sub-area

- **Predicted yield reduction over the season**: estimated yield reduction based on the average yield response factor used in equation 4.8
- **Predicted yield reduction considering the stages of growth**: estimated yield reduction with yield response factor for each stage of the crop growth, and yield reduction calculated for the season based on equation 4.9

For site-specific irrigation, it was impossible to estimate the water stress with annual, monthly, or weekly averaged values. The analysis required daily climatic information of evapotranspiration and rainfall. A method that uses seasonal values cannot be used in this study, since it is unclear how averaged climatic information values should be distributed over the period of study. For example, evapotranspiration of 731.66 mm for the study period in 1998 and 457mm of precipitation in the same period would require 274mm (731 – 457) of water to balance the water requirements. However, this number may only be correct if the rain was equally distributed over the period of analysis, which is unlikely. If most of the water came as rainfall at the beginning or end of the period, the water requirements would probably surpass that value, coming to a value close to the total evapotranspiration for the period (731.66 mm). Further work can incorporate seasonal climate weather as a way to forecast the expected yield, once a reliable distribution method is found. The use of average or seasonal weather information would allow the SSIS to be used in locations where daily weather information is not easily found.

Merging management units

The results of the merging of the management units are presented in figure 5.7. The possible layout configurations that were evaluated are shown, along with the 36



MMU	ABBREVIATI	Layout 1	Layout 2	Layout 3	Layout 4	Layout 5	Layout 6
		mm/m					
1	ChA	225.74	185.6	180	177.8	159.8	131.7
2	CoA	177.67	185.6	180	177.8	159.8	131.7
3	StA	171.75	171.75	171.75	177.8	159.8	131.7
4	BuA	50	50	50	50	50	131.7
5	ToA	121	121	121	121	159.8	131.7
6	CoA	177.67	177.67	180	177.8	159.8	131.7

Figure 5.7. Layouts of possible field management for site-specific irrigation based on AWHC resulting from the merging algorithm.

AWHC values used as inputs for the irrigation schedule. As shown in figure 5.7, one management unit was merged, one step after the other, until the whole field was treated as a uniform management unit with an average AWHC for the whole field of 131.7 mm/m. Layout 1 was the completely site-specific irrigation management, where each soil-mapping unit was treated as a different irrigation management unit. Layout 2 starts with as layout 1, then merges the Chewacla soil-mapping unit with one of the Congaree soil units, based on the spatial location and the AWHC criteria. The Chewacla soil unit was first selected for merging because the area of the unit was smaller than the pre-defined one-hectare threshold value, even though for tomatoes this area was probably profitable enough to be treated separately. Comparatively, soil-mapping unit 1 had high cost and required a high price for tomatoes to break-even. For layout 3 the other Congaree soil unit was added to the already merged areas. To form layout 4, the State soil unit, which had the AWHC value closest to the averaged AWHC of the merged areas, was incorporated, reducing the average value of AWHC for the merged areas. At this point three management units were differentiated for this layout: 1) the Congaree-Chewacla-State units with a high average AWHC value (178 mm/m); 2) the Toccoa soil-mapping unit with an intermediate AWHC (121 mm/m); and 3) the Buncombe soil-mapping unit with a very low AWHC (50 mm/m).

Layout 5 consisted of only two management units. The Toccoa soil-mapping unit with the intermediate AWHC was merged with the higher AWHC block (Congaree-Chewacla-State) forming a new management unit, leaving only the low-AWHC Buncombe soil unit to be treated independently. Finally, the last independent soil unit (Buncombe) was merged with the remainder of the field to form layout 6. This last layout

represented a uniform treatment of the field as a single management unit, with an area weighted average AWHC of 131.67 mm/m.

Volume of water applied in alternate layouts

The distribution of water applied in the field for each layout over the years is illustrated in figure 5.8. It is difficult to discern any layout with distinctly different water usage. Even though there was no statistically significant difference among layouts (P> 0.73), layout 5 had the largest average annual water consumption (52,615 m^3). The average water applied between the site-specific management strategies versus the uniform application was significantly different at the 90% confidence level (Appendix E). From figure 5.8, the water amount for the different layouts varied depending on the year. The depth of water applied increased from the uniform management layout to the site-specific management layout (layout 6 to layout 1) in 1971 (the first year of the study data); then in 1972 the pattern of water application was reversed with the water application increasing from the site-specific layout to the uniform management layout (layout 1 to layout 6). This suggests that the amount of water used was an interaction of the available water holding capacity of the soil and the climate pattern during the season, especially the ET demand and rainfall frequency and amounts.

The effects of climate on the water balance are shown in figures 5.9 to 5.12. For illustration purposes, two different management units (MMU_4 and MMU_5), considering site-specific (layout 1) and uniform irrigation (layout 6) treatments, for two years (1971 and 1972) were selected. Depending on the ET demand and rainfall frequency and amounts, the pattern of water consumption changed from one year to the other.

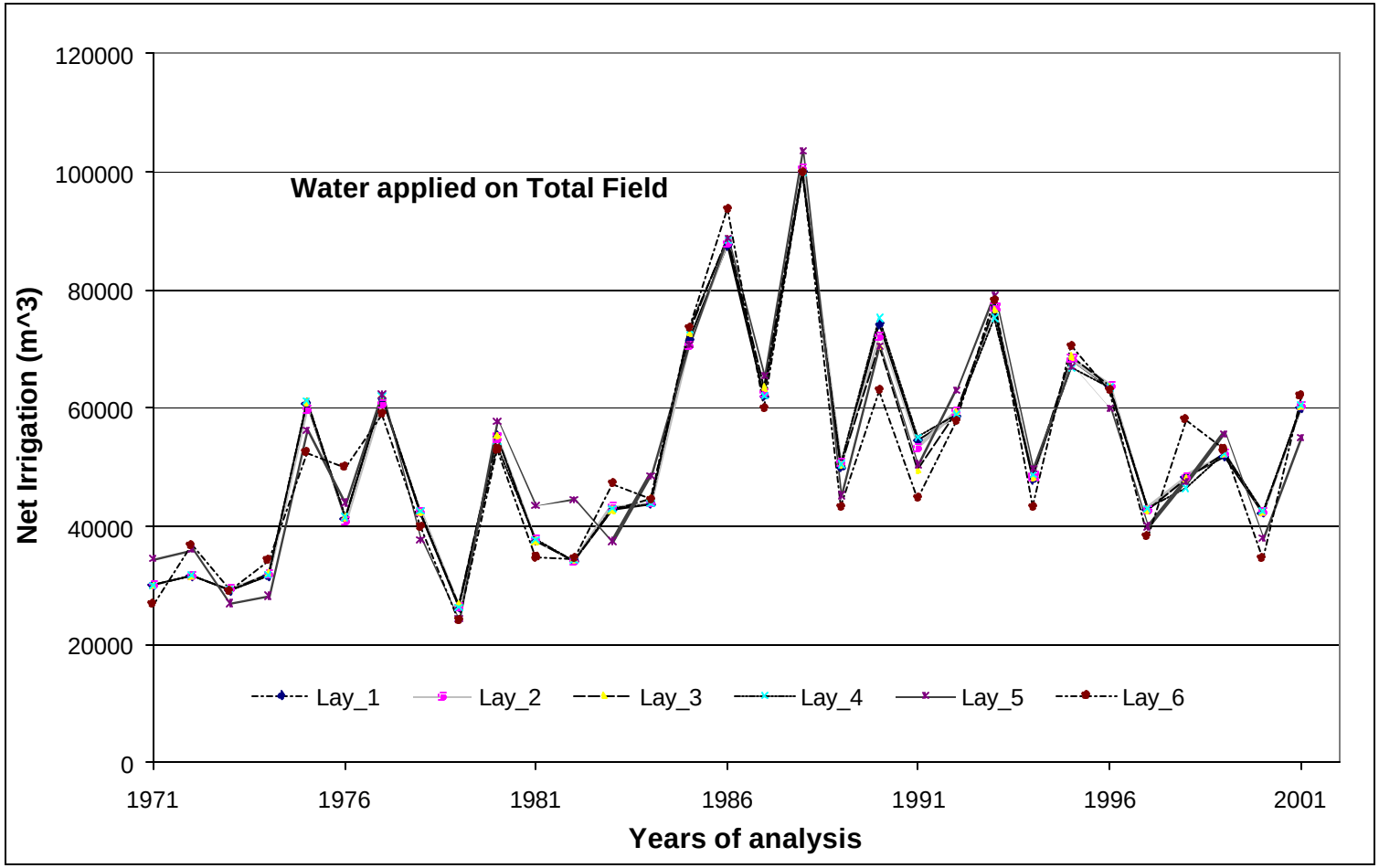
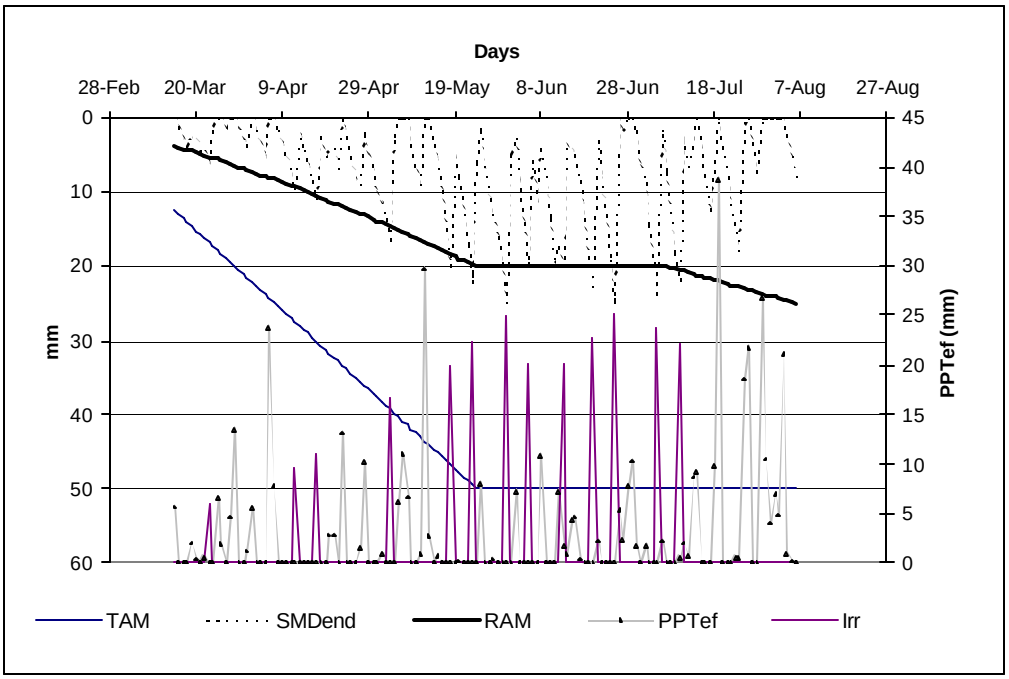
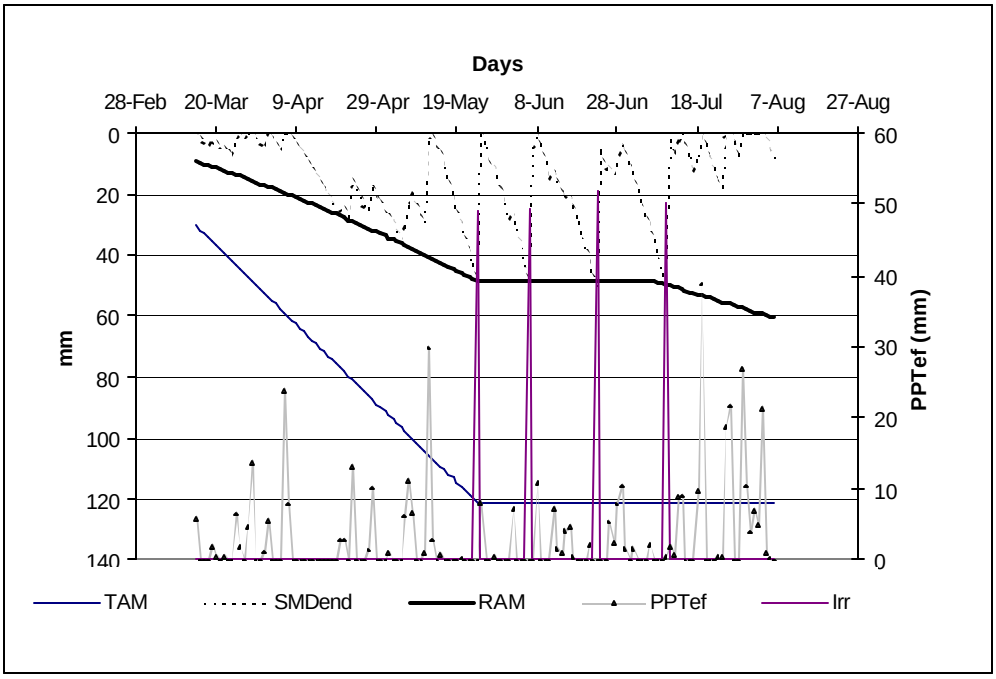


Figure 5.8. Predicted water applied by the site-specific irrigation schedule for the several irrigation management layouts over the years of analysis (1971 to 2001).

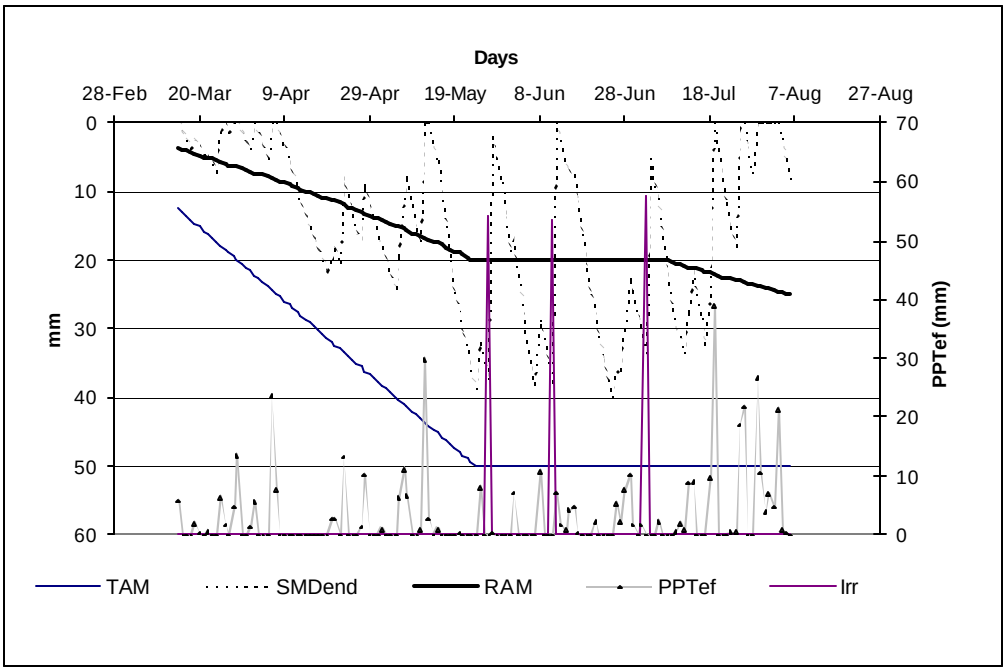


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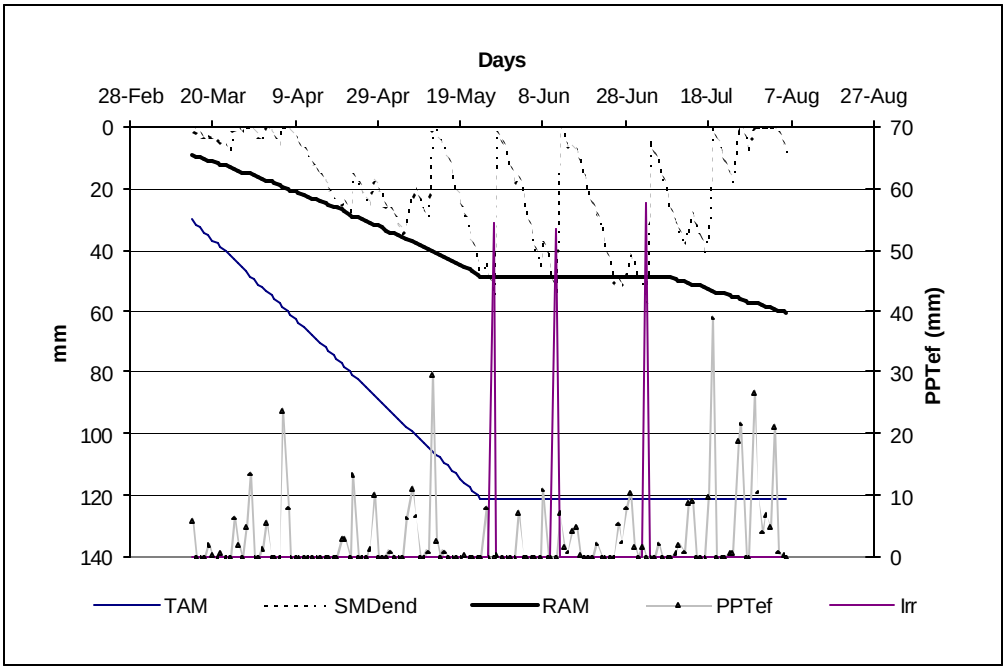


b)

Figure 5.9. Irrigation water balance: a) MMU_4 with 244 mm of water required for the season; b) MMU_5 with 200.5 mm of water required for the season, 1971 rain and ET data, layout 1 planting 3/15/71.

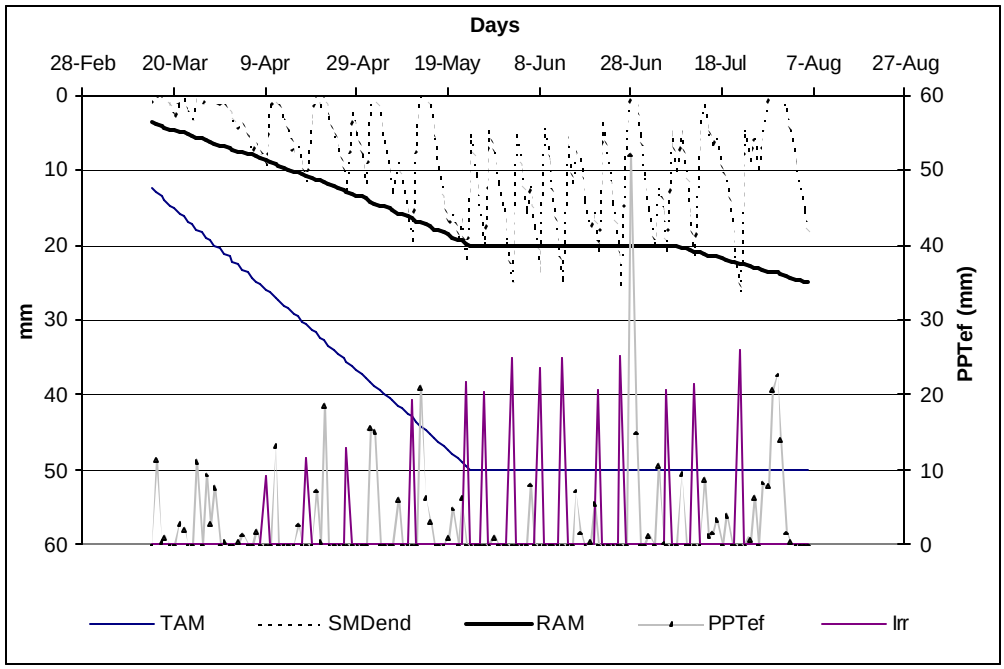


a)

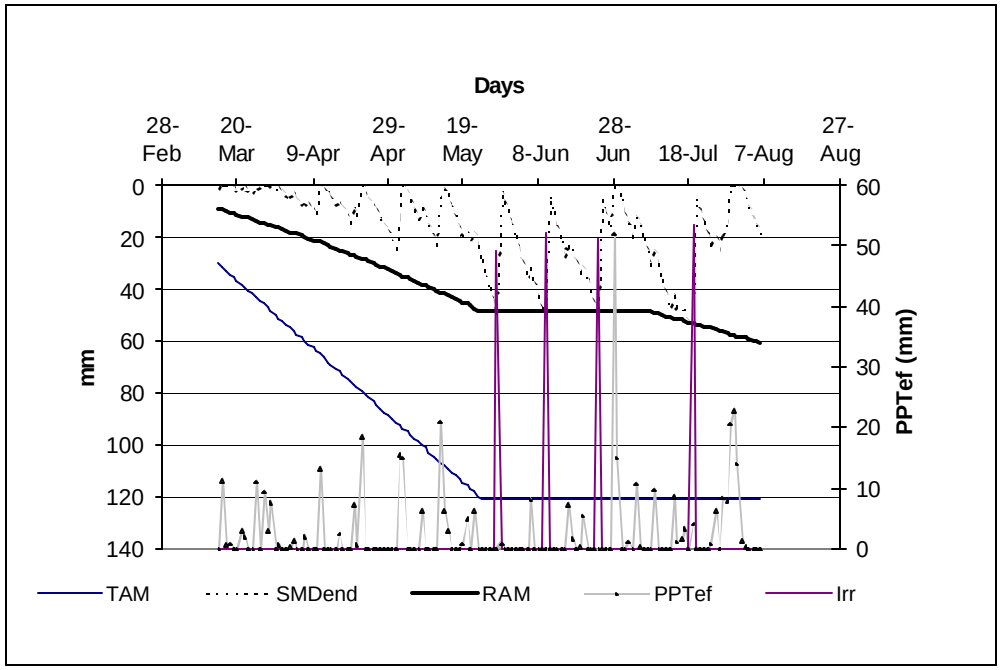


b)

Figure 5.10. Irrigation water balance: MMU_4 with 165.3 mm of water required for the season; b) MMU_5 with 165.3 mm of water required for the season, 1971 rain and ET data, layout 6 planting 3/15/71.

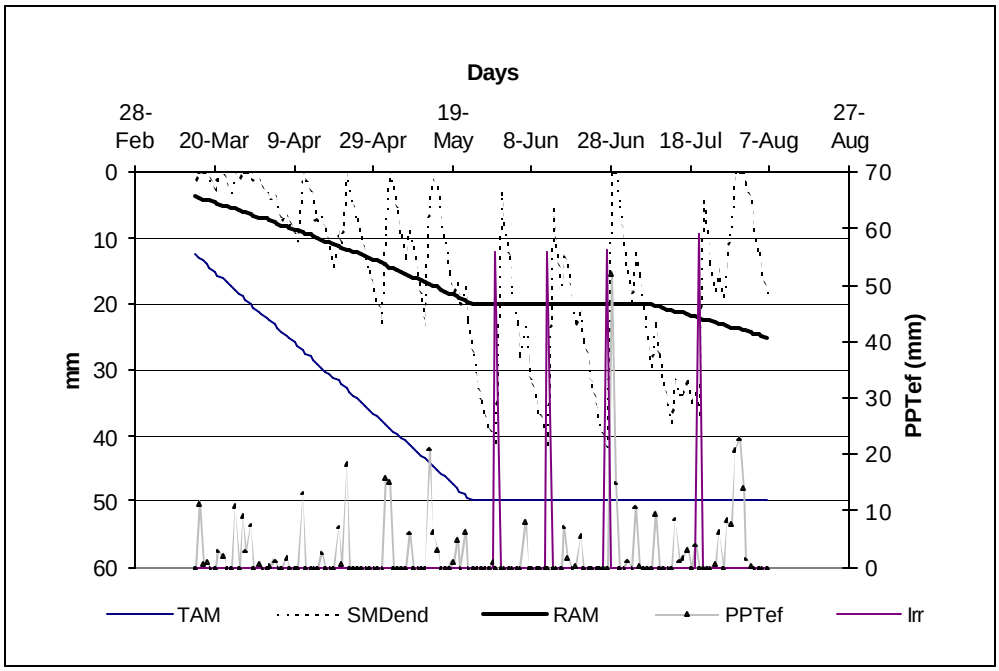


a)

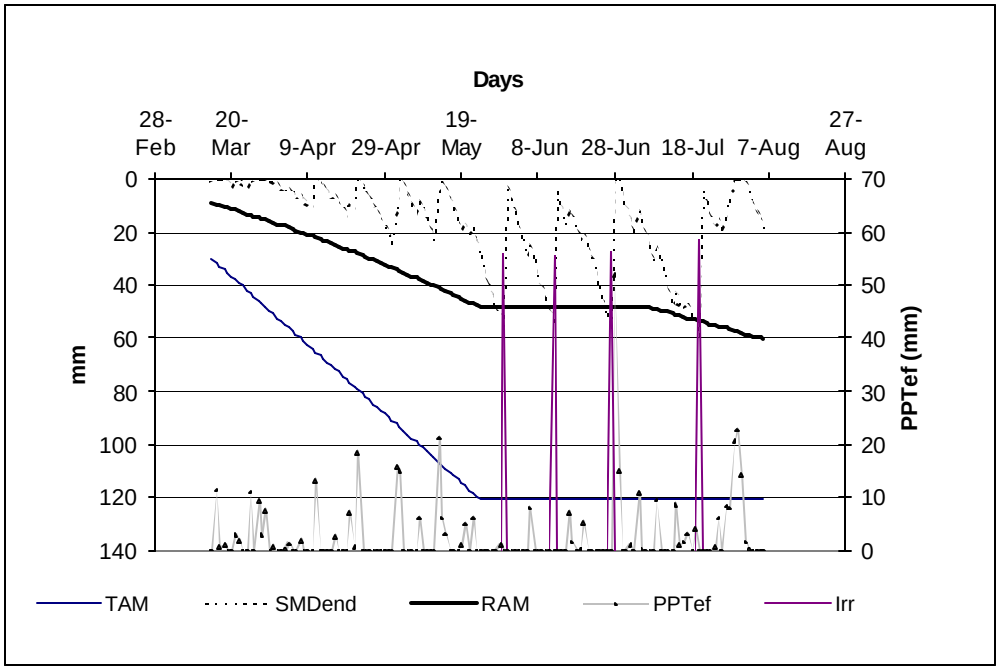


b)

Figure 5.11. Irrigation water balance: MMU_4 with 282.3 mm of water required for the season; b) MMU_5 with 205.9 mm of water required for the season, 1972 rain and ET data, layout 1 planting 3/15/72.



a)



b)

Figure 5.12. Irrigation water balance: MMU_4 with 226.8 mm of water required for the season; b) MMU_5 with 226.8mm of water required for the season, 1972 rain and ET data, layout 6 planting 3/15/72.

As observed in figures 5.9, both management units required more water applications for layout 1 (site-specific), compared with the amounts required for the same units when treated as layout 6 (figure 5.10) using the same data set (1971). For MMU_4 in layout 6 (figure 5.10), the soil moisture depletion went beyond the readily available moisture, causing reduction in yield due to water stress.

For the 1972 climate data set, the two irrigation management layouts were compared and MMU_4 had the same pattern of water consumption as for 1971, i.e., the site-specific layout consumed more water than the uniform treatment. For MMU_5, the uniform application (figure 5.12) had a higher water demand than the site-specific layout (figure 5.11). For the 1972 data set, the site-specific management had higher yield with less water consumption. The reduction in applied water was because under layout 1 (figure 5.11), the third irrigation (51.1 mm) occurred on June 24. On June 28 precipitation (74.2 mm) replaced most of the water evapotranspired during the 4-d period. For layout 6 (figure 5.12) with the water balance based on a larger AWHC, the model calculated that more water was stored in the soil profile. This caused the third irrigation (56.3 mm) to be postponed until one day before the rainfall, therefore less storage was available for the precipitation; making less use of the rainfall water. The rainfall water, in this last case, was assumed lost in the system, since the soil was close to field capacity. This illustrates how the water balance was dynamic in terms of adopted strategies and climate pattern.

Crop yield

Even though the amount of water applied over the years was nearly the same for the different layouts, tomato yields were significantly different among the six layouts

($P<0.0001$). The yield in an area was dependent on the layout, as shown in figure 5.13. Layout 6 consistently had lower production than the other layouts. Layout 5 also had slightly reduced production. The irrigation management did not significantly affect the other layouts. Layouts 1 through 4 did not show a statistical difference in average production using the Tukey-Kramer test with $\alpha = 0.05$ (Appendix E).

Although layout 6 used almost the same amount of water as the others layouts, the yield reduction can be explained due to the drastic yield reduction on the Buncombe soil, which had a very low AWHC (figure 5.14). This soil required frequent application of water in order to maintain high yields. Often, water applied in large volumes and at lower frequency for layout 6 was assumed lost as runoff or deep percolation within this area. Figures 5.10 and 5.12 show where the soil moisture depletion went beyond the readily available moisture, causing water stress in the Buncombe soil MMU_4.

Water losses

The total water losses over the years for the different layouts are presented in figure 5.15. Similar to the yield reduction, the worst situation was in MMU_4. The total water losses over the whole field (16.24 ha) averaged 3,840 m^3 (1 million gallons) per year, with estimated total water losses of 119,059 m^3 (31,4 million gallons) over the 31 years of data. Most of this water loss occurred in MMU_4, when treated as a uniform management unit with the rest of the field (layout 6). The average annual water loss in MMU_4 alone was 3,812.8 m^3 (1 million gallons) in layout 6.

While the water loss was indirectly accounted for in the cost of fuel and lubricants, there was no other penalty charged to applying excess water. If irrigation was applied shortly after a rain, or part of the field had the soil moisture profile close to field

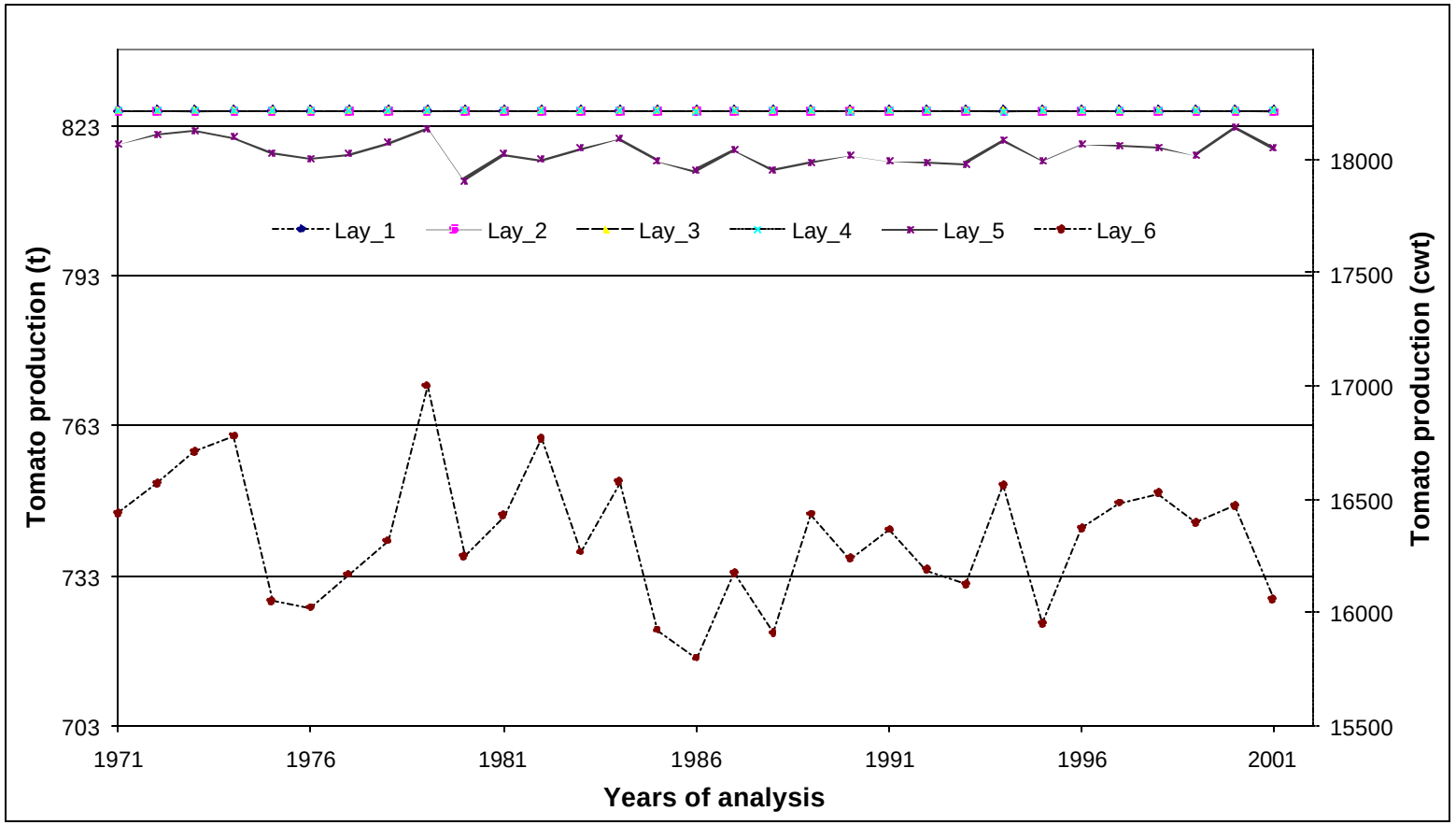


Figure 5.13. Predicted tomato yield based on maximum of 50.85 ton/ha (453.75 cwt/a) for the different field irrigation management layouts, over the years of analysis (1971 to 2001). Note: due to small variability in layouts 1 to 4, they visually overlay on the graph.

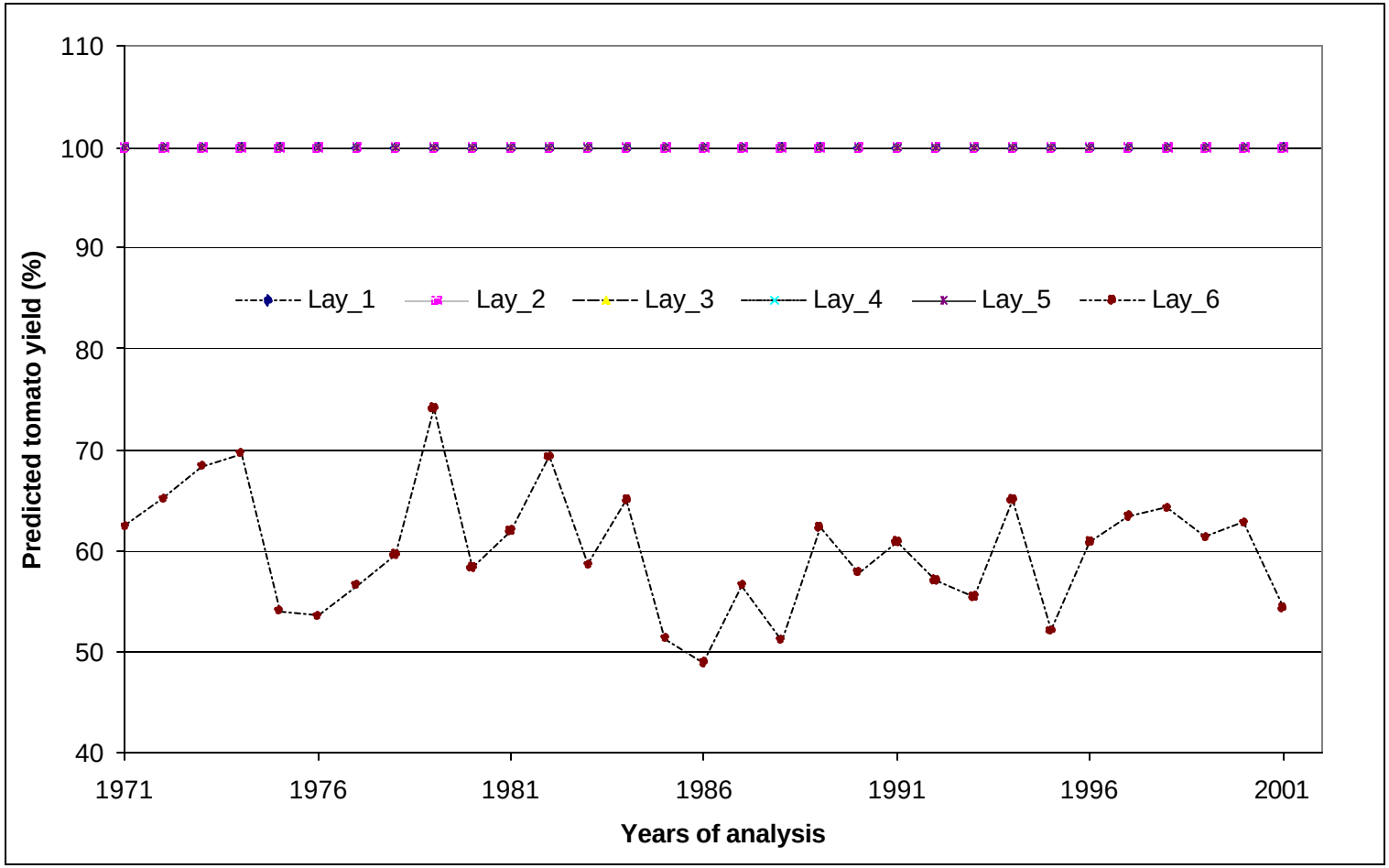


Figure 5.14. Predicted yield as a percentage of the maximum yield for MMU_4 with the different irrigation management layouts. Note: layouts 1 to 5 had no difference at this management unit so overlay each other.

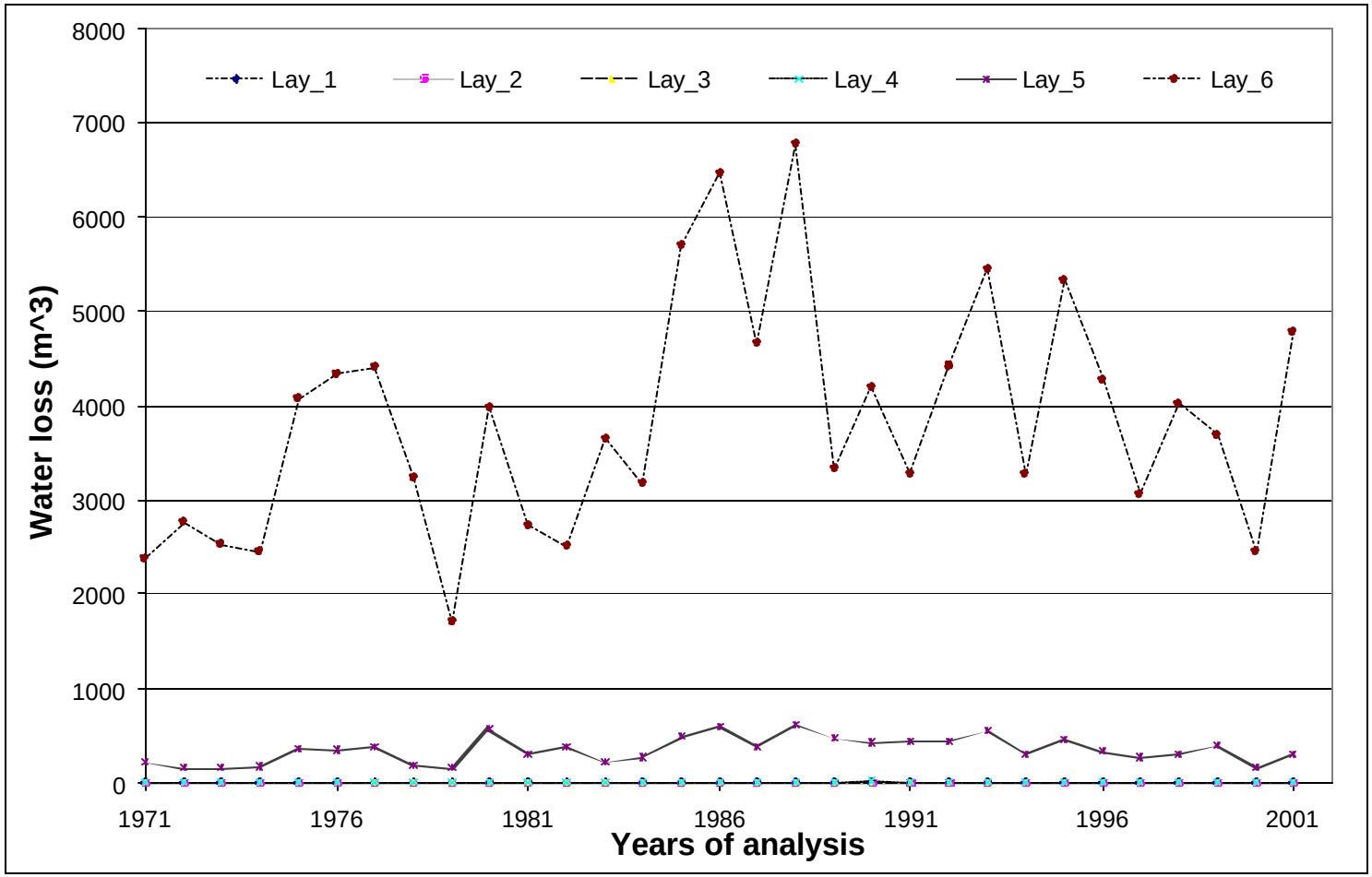


Figure 5.15. Predicted water losses for the different field irrigation management layouts, over the years of analysis (1971 to 2001). Note: layouts 1 to 4 had minimum water loss and overlay each other.

capacity, the excess irrigation water could have reduced the yield, due to lack of oxygen on the root zone, if the soil was poorly drained. Also, excess water (over-irrigation) can cause leaching of nutrients reducing the yield, with the nutrients leached ending up damaging the environment. In not accounting for the excess water, the model was conservative relative to the benefits to the site-specific irrigation. If water losses were incorporated into the analysis, the benefit of the site-specific irrigation would undoubtedly be even greater than shown in this analysis.

Net return results

Gross return

The net return, as discussed in previous chapters, was defined as the total revenue minus the total cost. The total revenue was calculated from the first part of equation 3.4, with the corrected year-to-year tomato prices from table 4.2. The yield was dependent on the irrigation management layout. The estimated yield for the SSIS was calculated with equation 4.9. The gross return incorporated the variation found in the year-to-year tomato prices (table 4.2) and the variation in estimated tomato yield, which was dependent on layout and the weather patterns (figure 5.13). The year-to-year gross return values and their descriptive statistics are listed in Appendix D. Figure 5.16 illustrates the expected gross return for the different irrigation management layouts. Layout 6 shows consistently lower gross returns than the other layouts. This result is in accordance with the lower tomato yield for layout 6 (figure 5.13). It was expected that, for the same tomato prices, layout 6 would have a lower gross income due to the lower yield in MMU_4 under this layout. This was the case, as the average reduction in gross return in layout 6 was

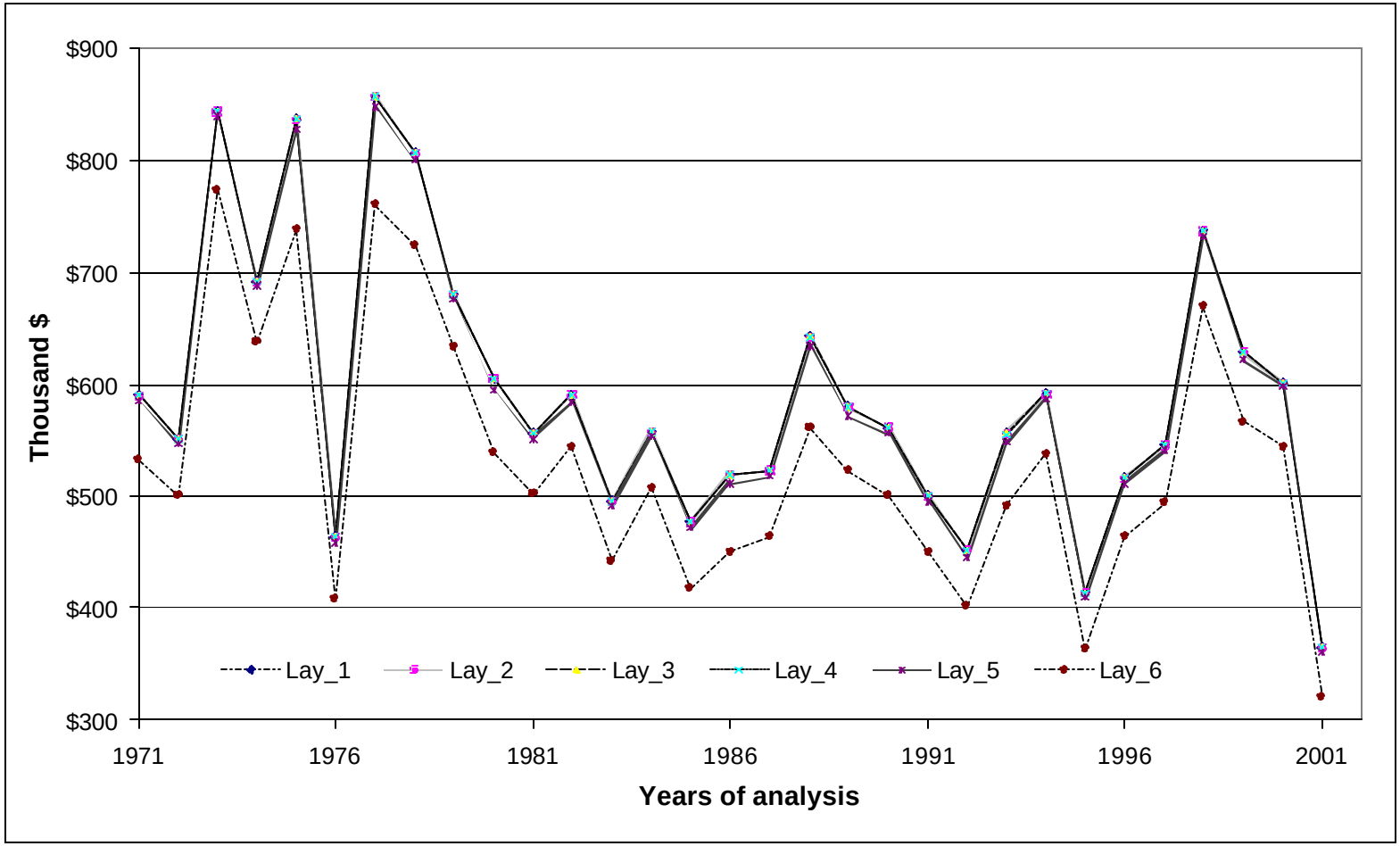


Figure 5.16. Gross return of tomatoes for field in Cocke County for the different layouts over 31 years of analysis. Note: layouts 1 to 5 had minimal differences and are therefore difficult to distinguish in the figure.

approximately 10% compared with the values for layout 1, which had the maximum gross return for most of the years, based on Friedman's chi-square test (Figure 5.17). Overall, layout 1 and 3 had the highest gross return for most of the years. Thus, the question to be answered is the same as that asked in chapter 3 -will the increase in yield (ultimate gross return) cover the extra costs for site-specific irrigation?

Costs

To identify the total cost, a crop budget for tomatoes was used. The crop budget was modified for this case study for site-specific irrigation management as described in Chapter 4 and presented in Appendix B.

The total cost of crop per year, as defined in Chapter 4, was $150,600 ($9,273 /ha). The cost of the fuel and lubricant was proportional to the amount of water pumped, or net water applied (Appendix D). A fixed price of fuel of $0.396/l ($1.50/gal) was assumed. The computation proceeded as described in Chapter 4, with an 18.6-kW (25-hp) pump and an estimated flow of 28.4 l/s (450 gpm). The standard deviations of the estimated fuel cost values were high, and followed the variation observed in the water applied. The costs of fuel and lubricants are presented in figure 5.18. Based on the specifications above, the annual average cost of fuel and lubricants was approximately $2,600 for the different layouts. Of this value, on average of $167 was expended unnecessarily on layout 6. The cumulative cost of the fuel and lubricant expendedunnecessarily on this field for layout 6 over the 31 years of analysis was $5,195; this was the cost relative to the pumped water that was lost on that layout.

The cost of harvesting was dependent on the production, with the harvest costs following the predicted yield. The cost of harvesting during the years for the different

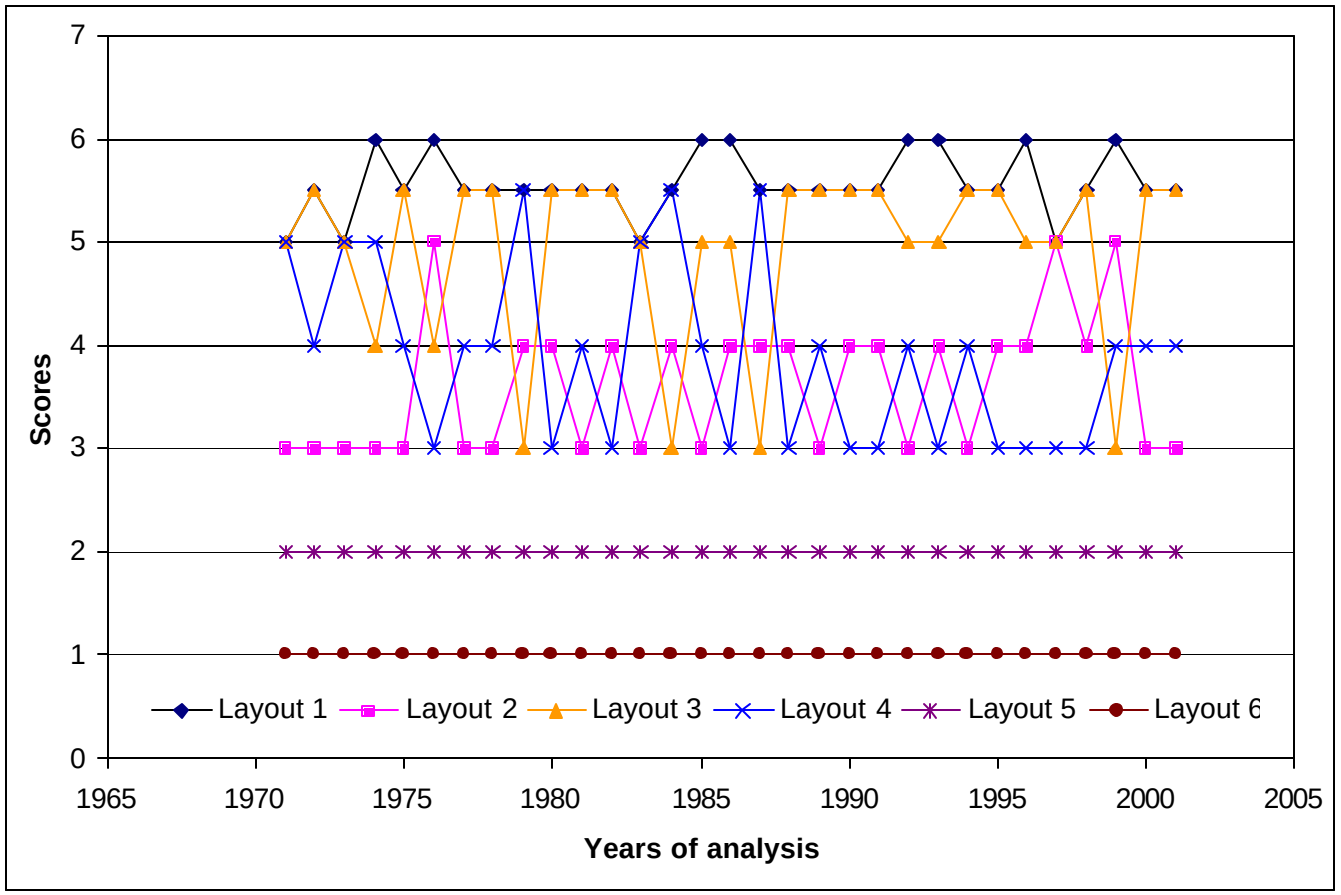


Figure 5.17. Friedman's chi-square scores for gross returns. Lower scores represent smaller gross returns; high scores represent large gross return, layouts with same scores are not different (P <0.0001).

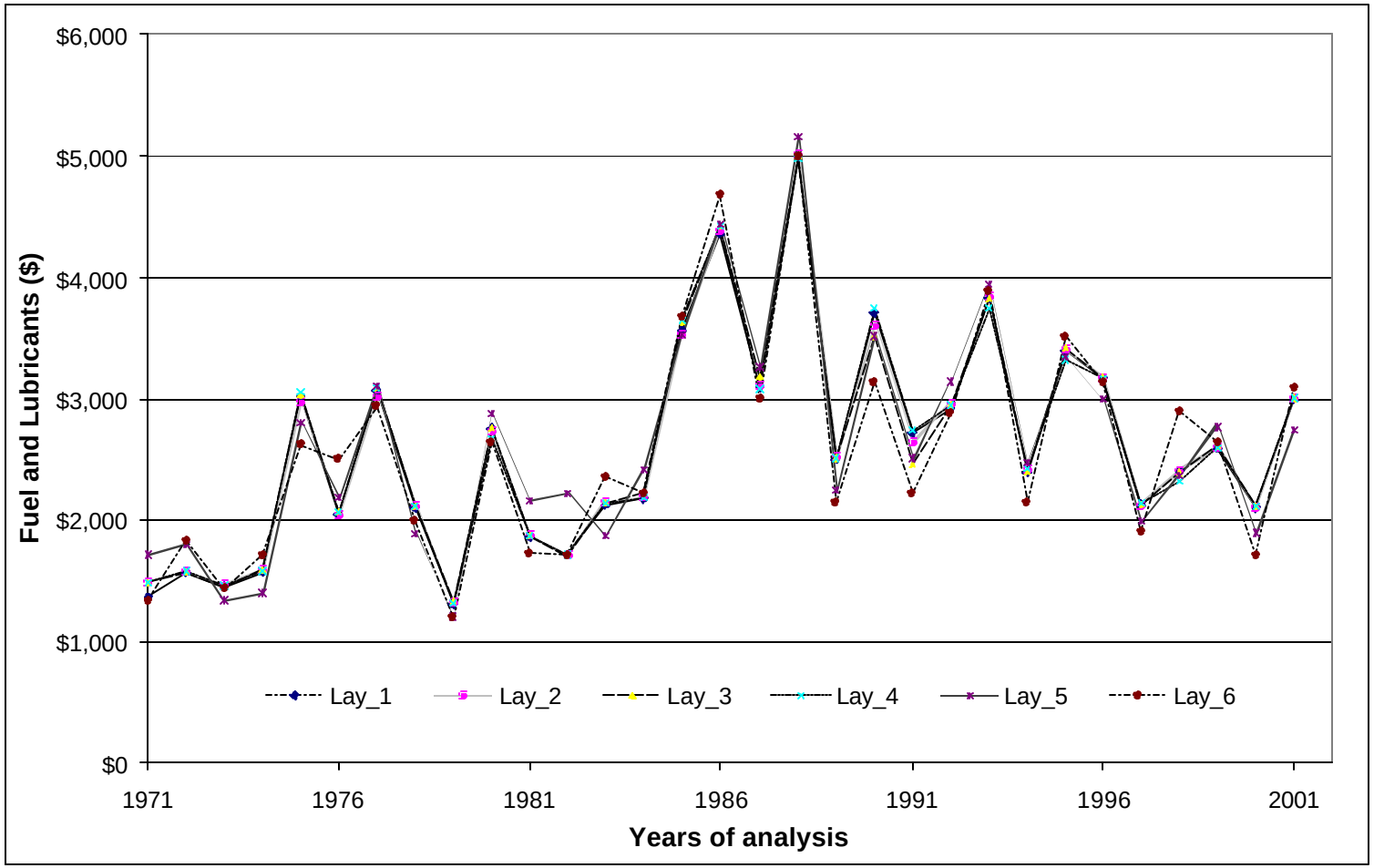


Figure 5.18. Annual cost of fuel and lubricant for each irrigation management layout over the 31 years of analysis.

management layouts is shown in figure 5.19. The price of labor was estimated as $0.176/kg ($0.08/lb) as given in the tomato budget. The descriptive statistics are given in Appendix D. The harvest labor in layout 6 was on the average 10% less than for layout 1; representing a savings in harvest cost of $15,777, compared to a respective $60,344 reduction in the gross income. Clearly, for the uniform irrigation management layout (layout 6) to be competitive with the other layouts, the savings in the site-specific costs must surpass the decrease in gross return. The direct relationship between production and harvest cost caused the average value to decrease for the uniform soil management (layout 6).

The remaining costs of labor set-up, headlines, and control units were dependent on the layout and did not vary with the year (table 5.1). As shown in table5.1, most of the site-specific costs (such as set-up labor, headlines, and control units) increased with the number of management units. The relationship between the number of independent management units and increased number of units of some of these components such as hours of labor for set-up the system and extra headlines were shown in figures 4.4 and 4.5 as linear relations.

The combined average cost of these three terms added to the other average costs of fuel and lubricants, harvest, and crop costs showed that the averaged annual cost increased with the number of management units, making site-specific irrigation less attractive (table 5.2). However, the increases in average annual gross return for the site-specific layouts raise again the question – do the gains in benefits cover the extra cost of implementing site-specific irrigation, and which layout gives the best net return? Indeed, in general the increase in gross return was far superior to the extra cost of being site-

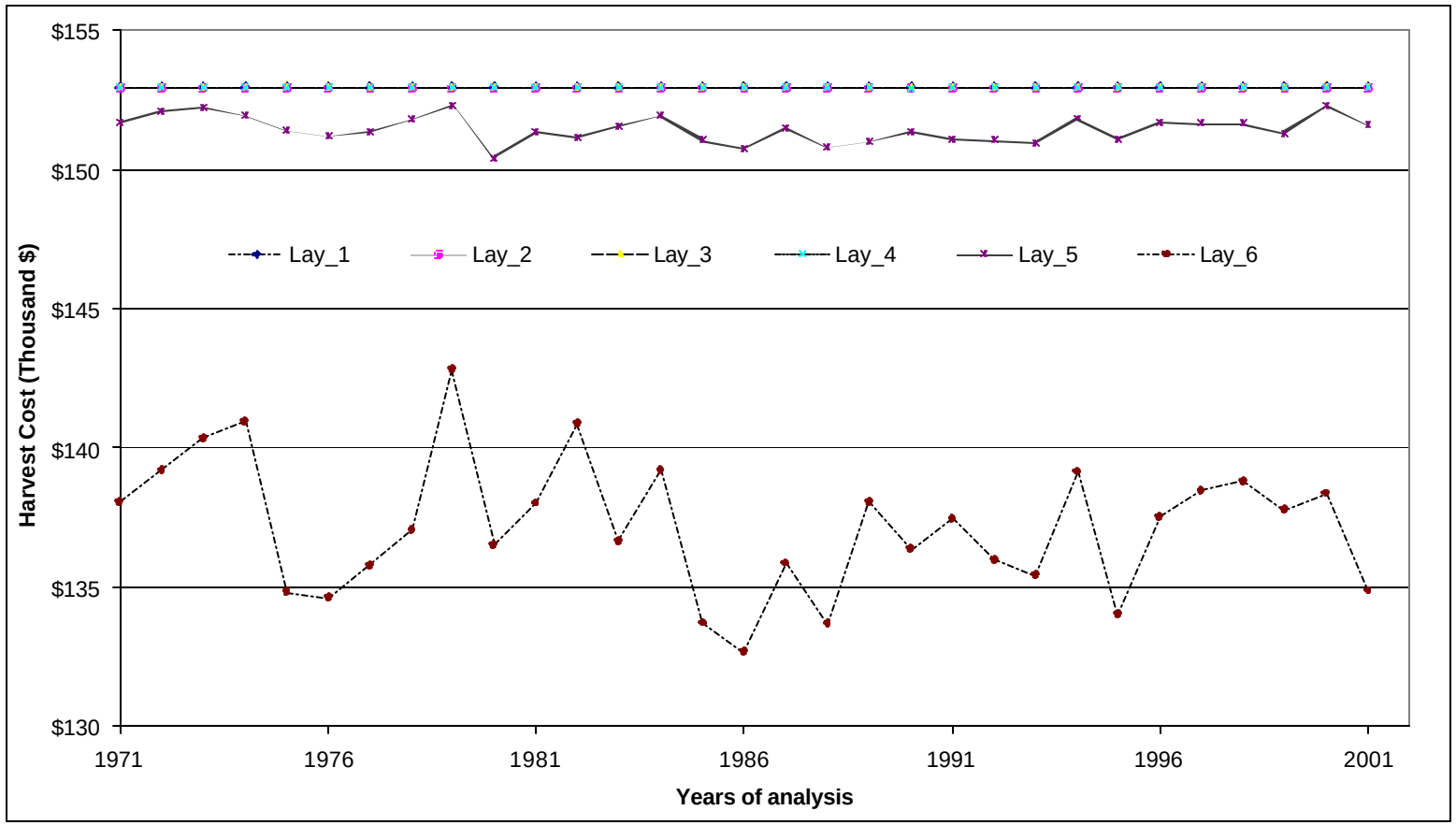


Figure 5.19. Annual harvest cost for each irrigation management layout over the 31 years of analysis. Note: layouts 1 to 4 were minimally different in harvest costs and cannot be distinguished in the figure.

Table 5.1. The annual costs for the different irrigation management layouts.

Labor Set-Up cost per layout

Layout	#MU	MMU_1	MMU_2	MMU_3	MMU_4	MMU_5	MMU_6	SL
				($)				
Lay_1	6	6	30	45	84	77	86	329
Lay_2	5	6	29	43	81	74	82	315
Lay_3	4	5	28	41	77	71	79	300
Lay_4	3	5	26	39	73	67	75	286
Lay_5	2	5	25	37	70	64	71	272
Lay_6	1	5	24	35	66	60	67	257

Cost of Headline per layout

Layout	#MU	HTC	Repairs	Depreciation	Interest	CH
				($)		
Lay_1	6	6955	209	2318	348	2875
Lay_2	5	6383	191	2128	319	2638
Lay_3	4	5811	174	1937	291	2402
Lay_4	3	5240	157	1747	262	2166
Lay_5	2	4668	140	1556	233	1929
Lay_6	1	4096	123	1365	205	1693

Cost of Control Unit per layout

Layout	#MU	Annual Cost	CCU
		($)	
Lay_1	6	72	433
Lay_2	5	72	361
Lay_3	4	72	289
Lay_4	3	72	216
Lay_5	2	72	144
Lay_6	1	72	72

Table 5.2. Summary of the average annual costs in 2001 dollars.

	Irrigation Layout					
Decision Variable	Layout 1	Layout 2	Layout 3	Layout 4	Layout 5	Layout 6
Annual Net Return	281,352	281,632	281,988	282,282	278,457	238,433
Annual Gross Return	591,155	591,108	591,149	591,114	585,483	530,810
Average Annual Costs	309,803	309,475	309,162	308,832	307,026	292,376
Costs of Crop per Area	150,600	150,600	150,600	150,600	150,600	150,600
Fuel	2,610	2,618	2,617	2,620	2,621	2,576
Harvest Labor	152,955	152,943	152,954	152,945	151,460	137,178
Set up Labor	329	315	300	286	272	257
Control Unit	433	361	289	216	144	72
Headline	2,875	2,638	2,402	2,166	1,929	1,693
Estimated Water Application	52,477	52,549	52,521	52,584	52,616	51,713
Estimated Yield/Area	454	454	454	454	451	423

specific (table 5.2).

As shown in table 5.2, to a point the average values of annual net return over the years of the study increased when considering all different soil types as individual management units (site-specific), compared to treating the field as a uniform single management unit. To be more precise, the net benefits of site-specific irrigation increased substantially from uniform water application until layout 4 was reached. For layouts 3, 2, and 1, the yield increased slightly from layout 4, but the increased costs of the extra equipment necessary for the more site-specific layouts made these less attractive than layout 4, which had the largest averaged annual net return.

Shown in figure 5.20 are annual net returns for the field with the different irrigation management layouts. Layout 4 had the largest average annual return. Additionally, the best year-to-year net return results were obtained with layout 4. Despite having the lowest annual cost, lower net returns were obtained with layout 6 compared with the other layouts, indicating that the gross return reductions had a larger effect on the final net return than did the costs. Net annual returns were also influenced by the year-to-year tomato prices, given the great variations in adjusted prices during the 31 years of analysis. Values associated with figure 5.20 are presented in Appendix D.

The reduction in the net returns for layout 6 were due to lower yield, and the yield reduction was very drastic in MMU_4 when using layout 6. The net returns for MMU_4 alone, considering the different irrigation management layouts, are presented in figure 5.21. As shown there, the net returns remained almost the same for all layouts except layout 6, since MMU_4 was maintained intact for all those layouts. For layout 6, the net

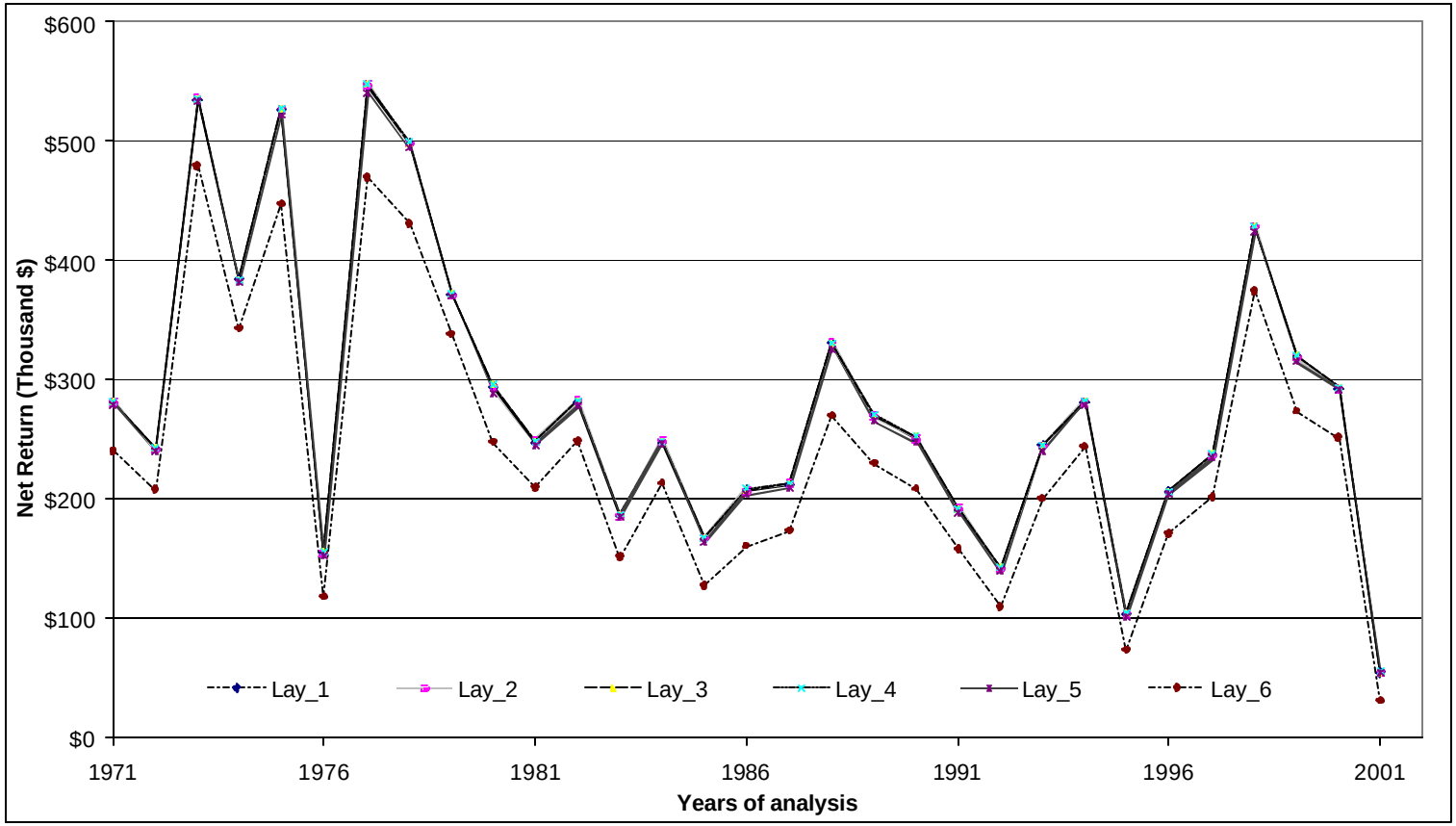


Figure 5.20. Annual net returns for each of the six irrigation management layouts over the 31 years of analysis considering year-to-year tomato prices. Note: layouts 1 to 4 are very similar and cannot be distinguished on the figure.

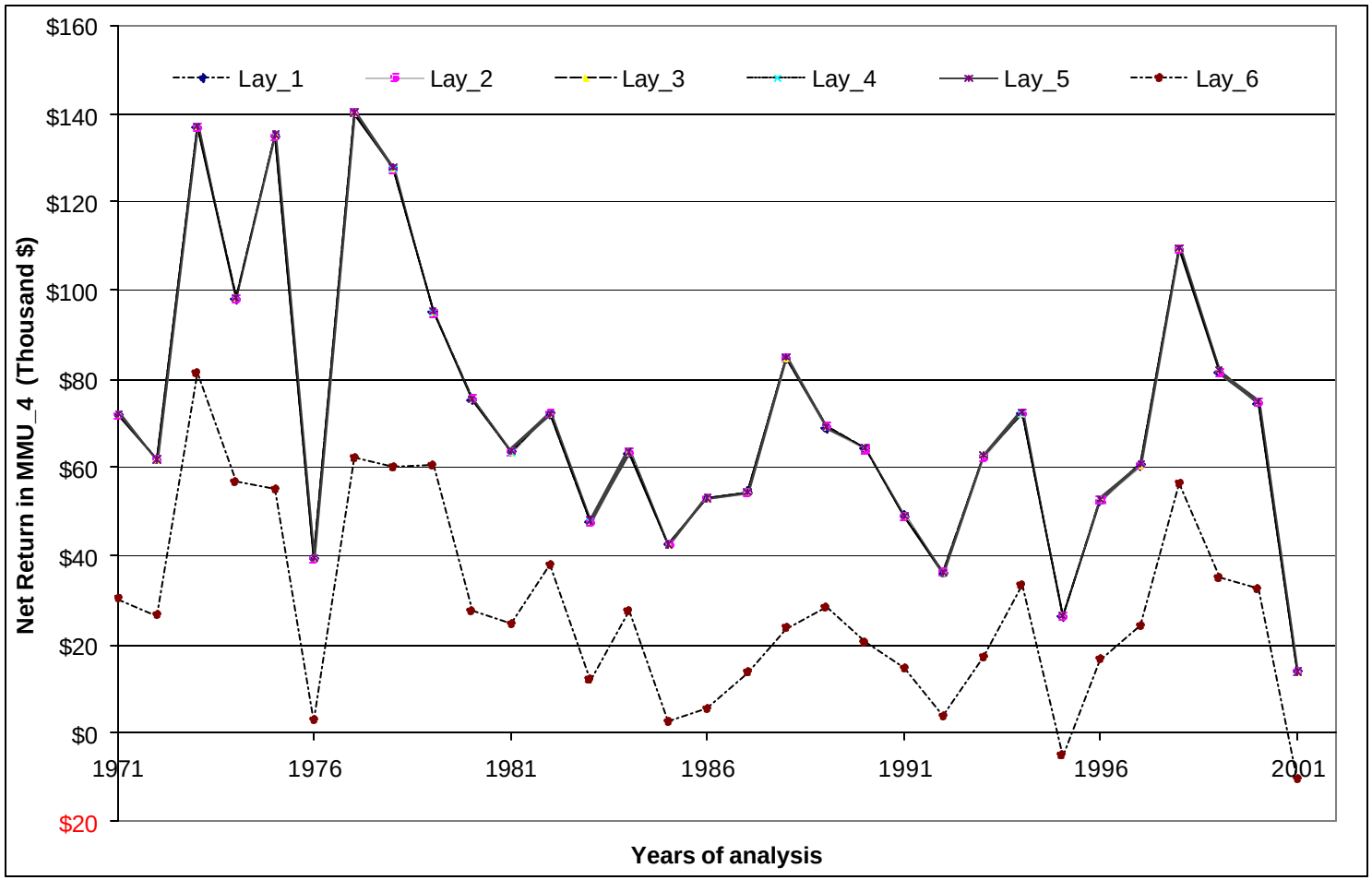


Figure 5.21. Annual net return for MMU_4 at the different irrigation management units over the 31 years of analysis. Note: layouts 1 to 5 are similar and cannot be distinguished in the figure.

returns for MMU_4 were drastically lowered. When tomato prices were lowest, in 1995 and 2001, the net returns for MMU_4 were negative $5,175 and $10,510. The average annual net return for layout 6 was only approximately 40% of the average net return for the other layouts.

Evaluation of best layout

The net returns were greatly influenced by gross returns, which was composed of expected yield and tomatoes prices. Evaluation of the net return for minimum, maximum, average, 50%, 25%, and 75% of expected tomatoes prices were performed. The objective was to verify the sensitivity of the net returns to the tomato prices, and to verify the net returns for a fixed price over the years, since most of the costs (cost of crop – CC) were constant in the analysis. The complete evaluation tables are found on the Appendix D. The different price scenarios that were tested had the same patterns, in terms of layout ordering, found for the year-to-year analysis of tomatoes price. The order of best net returns was layouts 4, 3, 2, 1, 5, and 6, according to Friedman's chi-square scores ranking ($P<0.0001$). Layout 4 had consistently high returns over the years compared with the other layouts, except for 1990 when layout 3 had the best net return (figure 5.22). This was caused by the higher yield reduction in MMU_3 under layout 4 for that particular year (17%). In fact, layout 4 would continue to be the layout of maximum net return even if the costs of the control units (CCU) increased by 100% (to $144/unit), as can be inferred from the average annual net returns in table 5.2.

Another important evaluation was the expected break-even prices of tomatoes required for the gross return to at least cover the costs of production. The tomato prices

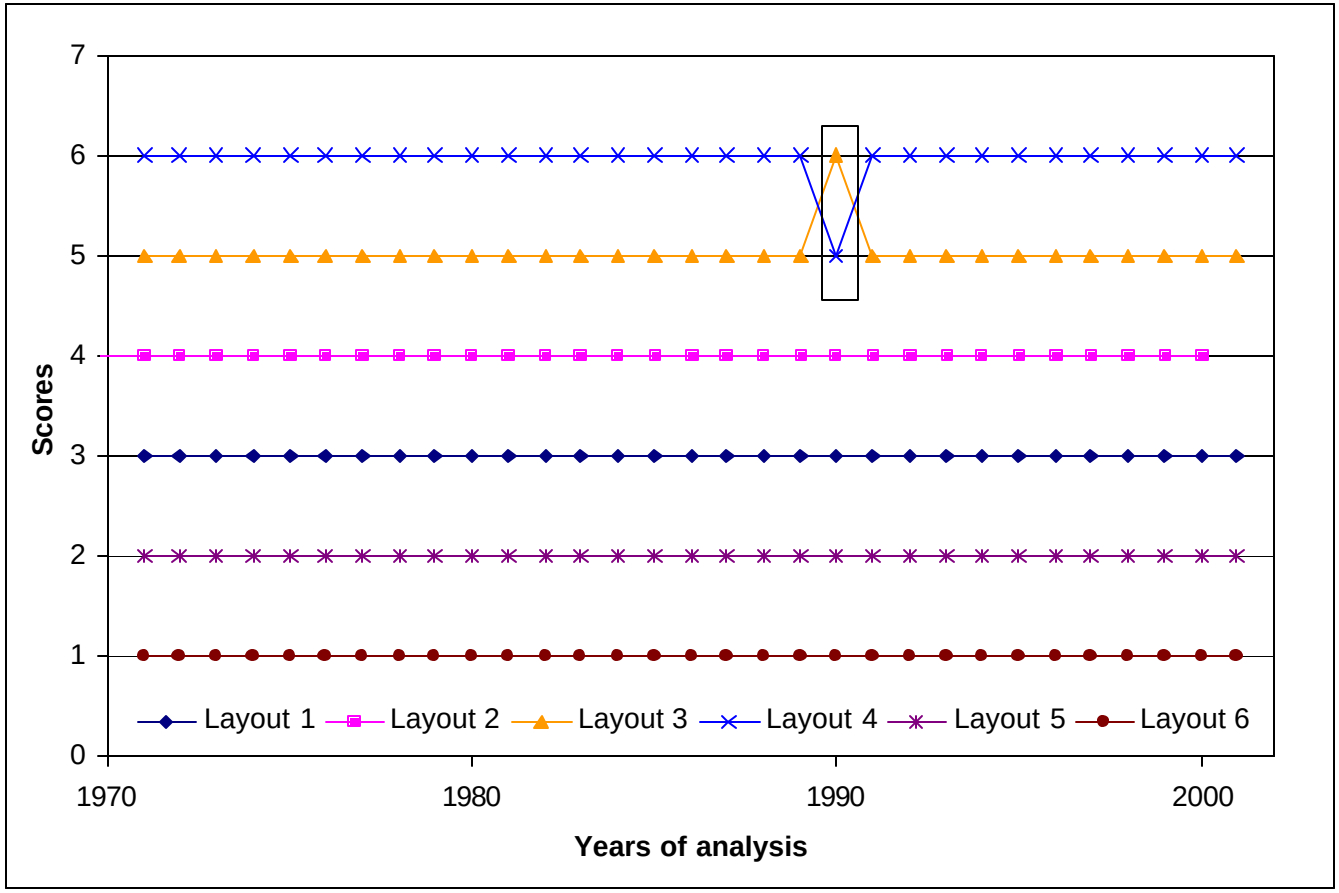


Figure 5.22. Friedman's chi-square scores for net returns. Lower scores represent smaller net returns, higher scores represent higher net returns (P <0.0001).

required to break-even, with the total tomato costs, for each layout are presented in figure 5.23.

From figure 5.23 it can be seen that the minimum observed price for tomatoes over the 31 years ($20/cwt), was always above the required break-even price, so the observed tomatoes prices (table 4.2) were high enough to cover the cost of site-specific irrigation in any year of the study. The maximum required break-even price was observed for layout 6 in 1986 ($18.36/cwt), the year in which production was the lowest.

The required price of tomatoes to cover the cost in MMU_4 is the same (approximately $17/cwt) for all of the layouts except layout 6. MMU_4 was treated individually for most of the layouts, but in layout 6 the area was merged with the others. The tomato prices required to break even with the associated costs were drastically changed due to the production reduction observed in this area under layout 6. The averaged break-even price to cover the costs under layout 6 was $22.75/cwt, which was above the minimum observed tomato price of $20/cwt (figure 5.24).

The cumulative probability of the expected tomatoes prices during the period of analysis is shown in figure 5.25. For example, a price lower than or equal to $25/cwt occurs 10% of the time during the 31 years of analysis. Conversely, a price of $25/cwt or higher occurs 90% of the time.

Combining information from figures 5.23 and 5.25, it can be shown that the minimum break-even price of $19.80/cwt in layout 6 was realized more than 97% of the time. In the same way, the maximum required break-even price of $26.10/cwt for the same layout, was realized only 88% of the time. For low-value crops, this number would be smaller. Thus, for a considerable percentage of time, say higher than 12%, the farmer

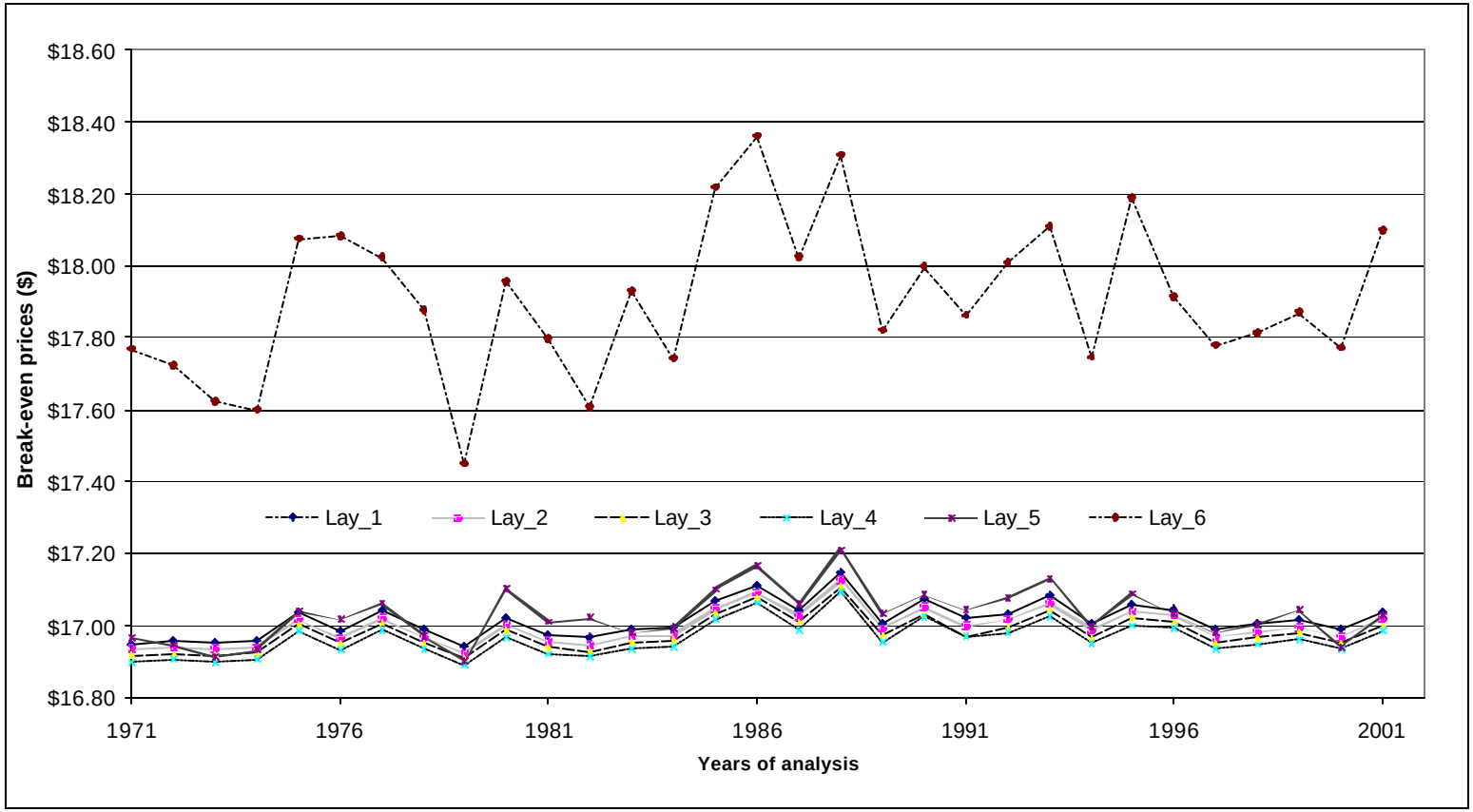


Figure 5.23. Required break-even prices for tomatoes to cover the costs of each irrigation management layout.

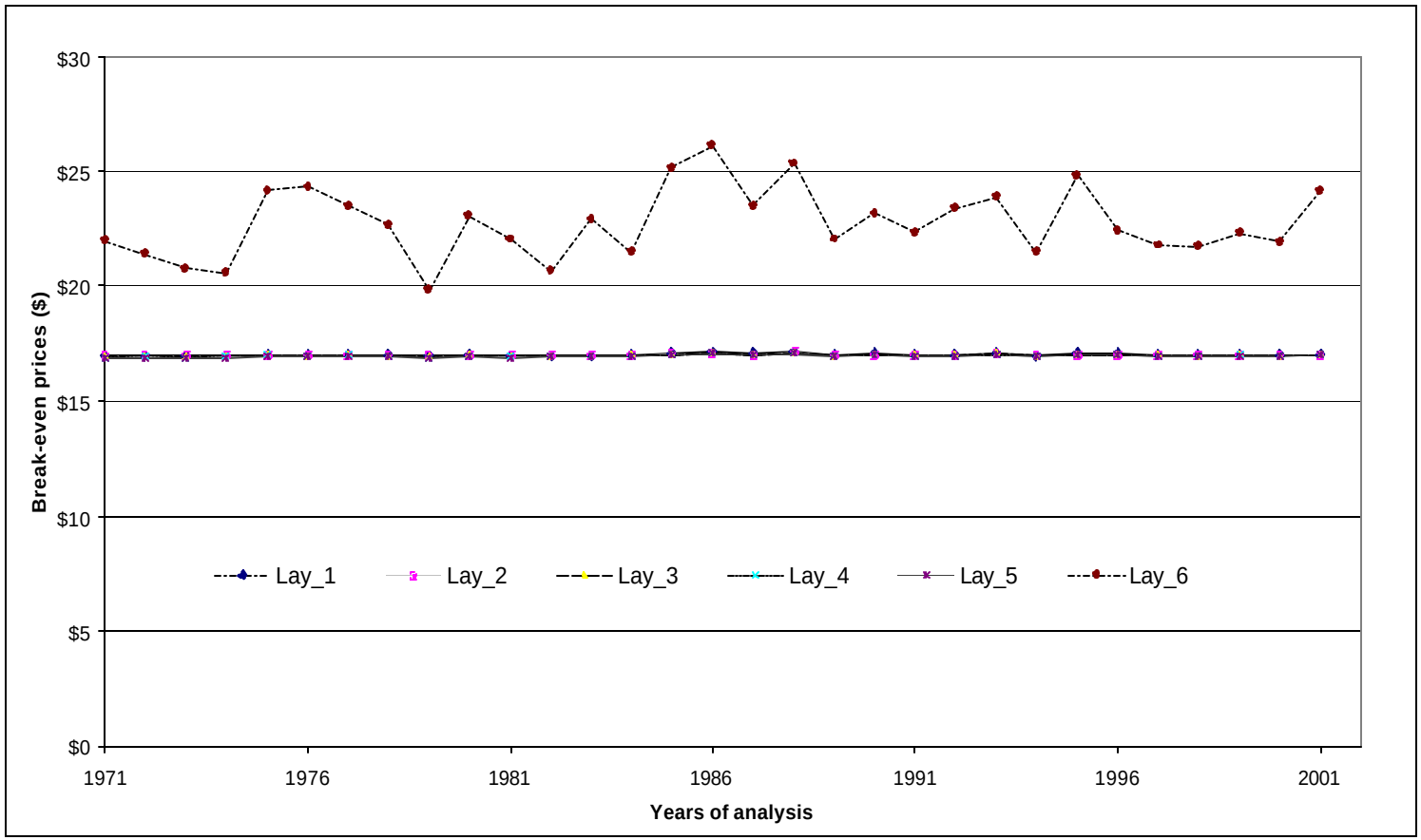


Figure 5.24. Required break-even prices to cover costs of site-specific irrigation management layout in MMU_4. Note: for this MU the required break-even price of layouts 1 to 5 are the same. Note: layouts 1 to 5 had minimal differences and cannot be distinguished from each other in the figure.

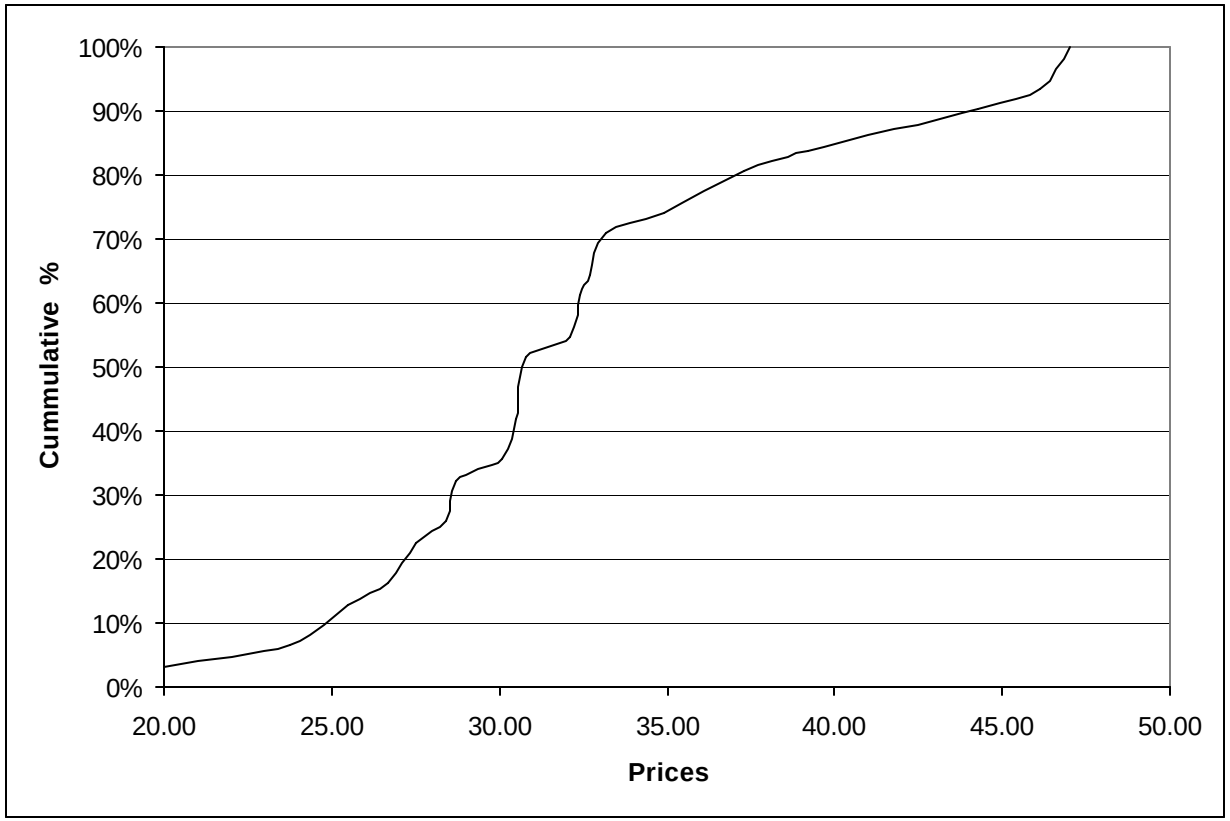


Figure 5.25. Cumulative probability of tomatoes price from values converted to 2001 prices (1971 to 2001 observations).

would have negative net returns in management unit 4 (MMU_4), if it were treated uniformly with the rest of the field.

For layout 5, the chance for a negative net return from MMU_4 was eliminated. In layout 5, MMU_4 was treated individually, so the yield for this sub-area under this layout was at the maximum. The fixed costs were close to the minimum value ($2,007 in layout 6). These conditions made the net return for MMU_4 the maximum possible for this layout. However, this was not the best layout for the whole field. There were small but significant yield reductions (in MMU_5) for layout 5 (figure 5.13). Because MMU_5 represented 23.5% of the total area of the study field, MMU_5 had a significant negative impact on the results for layout 5.

The site-specific layout 4 separated MMU_4 and MMU_5 from the merged units. These two units were treated as independent units in the field, with the yield maximized for each in terms of water demand. The water applications were also optimized for these two areas. The reduction in yield was minimal for the other merged (grouped) areas, given the relatively similar AWHC values. The increase in the fixed cost was basically attributable to treating MMU_5 as an individual area. The net return for the whole field was increased for layout 4, compared with layout 5. For the other site-specific layouts (1,2, and 3), irrigating the other soil-mapping units each as a single unit did not result in significant additional increase in yields. The extra cost to implement the different irrigation management treatments for these areas made layouts 1, 2, and 3 unattractive. The net return decreased going from layout 3 to 2, and from layout 2 to 1 (figure 5.22). For the reasons given above, even going from layout 4 to 3 was not justified. There was no significant increase in yield, but there were additional extra costs associated with

equipment and labor, and there was increased complexity in the irrigation system. Based on these factors, layout 4 was selected as the best layout for the case study.

There may be cases, however, in which net return would be maximized by not irrigating part of the field. In such a case, an incremental net return analysis might identify such areas. The incremental net return is the net return with irrigation minus the net return without irrigation. There may exist an area in the field with high AWHC that for most years produces a yield close to the maximum potential value, because high AWHC areas are less susceptible to rainfall frequencies given the larger soil moisture buffer. This was confirmed by the validation analysis, in which zones of high AWHC had the highest yields. In these high-yield areas, the increment in yield due to irrigation was small to none, and the extra cost of the irrigation system reduced the total net return (negative incremental net return). On the other hand, low-AWHC areas in the field were more susceptible to water deficits, and usually had low yields when not irrigated. The use of an irrigation system brought the yield close to the maximum potential value. The increase in yield may be large enough to make the incremental net return positive, paying the extra cost of the irrigation system. On the other hand, if a low-AWHC area is merged into a larger area as part of the optimum economic solution, it may be that the limited irrigation applied to this area is insufficient to raise the yield enough to pay the cost of irrigation. In this case, it may again be better to exclude the area from the analysis altogether. If a producer decides to irrigate only those parts of the field for which the incremental net returns are positive, the overall net return will be increased. An irrigation system designed for these areas in the field should be evaluated for the first hypothesis, of site-specific versus uniform irrigation. With the system designed, the same conceptual

framework developed in this dissertation could be used only for these irrigated sub-areas. The objective would be to decide if those areas should be treated alone, or grouped with a number of other sub-areas that had been selected as worthy of irrigation.

The hypothetical situation described here may occur for other crops such as soybeans, where the gross benefits are not so great when compared with the costs involved. In this case, the framework would first be applied to the whole field to estimate the yields and net returns for the alternative layouts. From the first analysis, areas with negative incremental net returns could be identified and excluded. The framework would then be applied on the remaining areas to find the best layout. In this specific situation, given layout 4, it may only be advantageous to irrigate MMU_4 and MMU_5. But a decision still would have to be made in the second analysis whether treating the two units alone or together as a uniform management unit is the better choice.

CHAPTER 6

SUMMARY AND CONCLUSION

A procedure to aid the decision-making process of selecting site-specific management units for irrigation has been described. The basic question was, should the field be treated as a whole (uniform application), or should certain areas in the field be treated individually (site-specific application)? The decision-making process also addressed the question of how many sub-areas should be considered independently, and how the field should be configured. The study methodology first identified the soil properties that affect irrigation system management, and used a framework to evaluate the effects of site-specific irrigation on production. A geographic information system (GIS) database was used in the decision framework to analyze the information for each management unit. The management units were first grouped with a merging algorithm to create different layouts. The merging algorithm took into consideration sub-area size, the Available Water Holding Capacity (AWHC), and sub-area location as merging criteria. Evaluation of each soil management unit in terms of water usage and crop yield when treated under each irrigation management layout was performed through a site-specific irrigation schedule (SSIS) and a yield-estimation model.

The irrigation schedule used in the decision framework was site-specific in order to address the varied AWHC in multiple areas within a field. The yield estimation model could have been any crop growth model with a water stress component; the model selection should be based on the availability of the model and the users familiarity with the model. Because the yield estimator had a decisive role in the final layout selection, it

is recommended that the yield-estimator be tested for the crop and field conditions under consideration before it is used in the decision framework.

The SSIS that was developed can be used with any crop growth model, either by integrating the code into the program, or by using outputs from the schedule as irrigation management input to the model. For yield estimation, a simple water stress function was used. The yield function that was selected has been frequently used in previous water deficit studies. Testing of both the SSIS and yield reduction function was performed.

The site-specific irrigation schedule model was verified against a well-known irrigation schedule model (CROPWAT). The outputs of both models were highly correlated ($R^2 = 0.95$), validating the integrity of the SSIS. The yield reduction function was also well correlated with actual yield data ($R^2 = 0.81$) for the field in the case study.

Results from the SSIS and yield estimator for each management unit within each layout for a data set of 31 years were used to reach the final decision about the best layout for the field. When tested for tomato production, the optimum layout, which produced the highest net return, was layout 4 with areas of high, medium, and low AWHC. A crop budget was used to compute all costs other than irrigation management for the tomato production. The irrigation management costs were customized to the site-specific and layout requirements.

The average annual costs increased from the uniform irrigation to the site-specific management layout. However, the loss of gross return exceeded the savings in costs for the uniform irrigation management layout (layout 6, net annual return = $238,433). The reduction in gross return for layout 6 was mainly caused by the large reduction in yield in management unit 4 because of the low AWHC. When MMU_4 and MMU_5 (areas of

low AWHC) were treated separately from the rest of the field, which had higher AWHC, the net returns were maximized (layout 4, net annual return = $282,282). Thus, layout 4 was the selected layout for irrigation management; the net returns for layout 4 would still be maximum even if the costs of control units were increased by 100%.

The yield estimation function used in this study assumed maximum yield of the crop, with no other factors (i.e., fertility, insects, disease, water excess) besides water deficit limiting the yield.

Some conclusions drawn from this study were:

- Integration of a site-specific irrigation schedule (SSIS) with a crop yield estimation model, and with GIS, formed a decision framework to successfully delineate management units for site-specific irrigation.
- The decision framework is general and can be used with any yield estimation model that includes water stress in the calculation of yield.
- Annual net return was increased by merging areas with similar AWHC, where the lowest AWHC was less than 3% different from the average. For areas with low AWHC and greater than 20% difference from the average, the annual net return was increased by treating the areas separately.
- For a case study of irrigated tomato production using 31 years of weather data, the decision framework was used to delineate site-specific irrigation of three areas in a 16.24-ha field that increased average net return by $2,700/ha compared to uniform irrigation of the whole field.
- For the case study, uniform management (layout 6) was the worst scenario, with the greatest water loss (average annual of 3,840 m^3), the lowest yield

(10% smaller on average), and the lowest net returns (annual average of $238,433).

Topics for further research

The study should be extended to other crops that are less profitable than tomatoes. The economic analysis in this study always showed positive net return values for the entire field with the assumption that there were no other constraints to yield besides water stress. The study should be extended to include other yield reducing factors.

The study should also be extended to other fields that have different soil mapping units and spatial relationships. An automated way to estimate the irrigation system design (hardware) based on the soil layout would speed the analysis and would give an easy way to determine headline costs. This additional step would also allow the search for better defined management unit shapes that would reduce the irrigation system hardware cost.

This analysis assumed that the whole field was irrigated, with the hypothesis testing whether areas in the field should be irrigated separately or grouped in order to maximize net return. There may be cases, however, in which net return would be maximized by not irrigating part of the field. In such a case, an incremental net return analysis might identify such areas.

This analysis was conservative in terms of not recognizing some of the benefits of site-specific irrigation, e.g., avoiding excess use of water that can inhibit crop growth and yield. To incorporate the excess water effect and other factors that may inhibit crop growth and reduce yield, modification of the yield estimation function or the use of a more complex crop growth estimator could refine the yield estimate.

For modifications of the yield estimation function, one suggestion is to manipulate the initial maximum value with which yield is estimated. This modification possibly can be done by using coefficients that account for other limiting factors. For example, in the case of excess water, the yield potential could be equal to 0.6 of its original value.

If the decision is made to select a more complex crop growth model, the model must have a water balance component. Despite better simulation of climate, management, and genotype interactions, complex models will require proper model calibration (parameter estimation), verification, and validation analysis before use.

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APPENDICES

APPENDIX A

EVAPOTRANSPIRATION ESTIMATION

A.1 Solar Radiation estimation

The solar radiation term was calculated with an equation developed by Allen et al. (1998). The procedures used to calculate missing data were incorporated in the code. This code was written in VB script, and can be run either in Excel or in any other Visual Basic related application.

```
Function myRs(Lat, Alt, n, Julian, Tmax, Tmin)
'
' myRs Macro
' Macro recorded 1/20/2003 by Carlos Wagner Oliveira

'
'Calculate Solar irradiance based on number of sunhine hours or Tmax and Tmin
Dim dr, sigma, ws, Ra, bigN As Variant

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
'Calculate Ra - extraterrestrial radiation
omg = Application.WorksheetFunction.Pi * Lat / 180
dr = 1 + 0.033 * Cos(2 * Application.WorksheetFunction.Pi * Julian / 365)
sigma = 0.409 * Sin((2 * Application.WorksheetFunction.Pi * Julian / 365) - 1.39)
ws = Application.WorksheetFunction.Acos(-Tan(omg) * Tan(sigma))
Ra = 37.59 * dr * (ws * Sin(omg) * Sin(sigma) + Cos(omg) * Cos(sigma) * Sin(ws))
bigN = ws * (24 / Application.WorksheetFunction.Pi)
'Case actual duration of sunshine is avaible
If n <> "" And n > 0 Then
myRs = (0.25 + 0.5 * (n / bigN)) * Ra
Else
 'Case Tmax or Tmin not available myRs = -99999
 If Tmax <> "" And Tmin <> "" Then
    If Tmax = -99999 Or Tmin = -99999 Then
       myRs = -99999
     Else
       'Case actual duration of sunshine not available
       'For inland site K = 0.16, for costal K = 0.19
       myRs = 0.16 * Ra * (Tmax - Tmin) ^ 0.5
    End If
 End If
```

A.2 Evapotranspiration estimation

Evapotranspiration was estimated by the Penman-Monteith equation presented in chapter 4. When solar radiation data, relative humidity data, and/or wind speed data were missing, they were estimated using the procedures presented by Allen *et al.* (1998). As an alternative, ETo was estimated using the Hargreaves equation. The code incorporates all these equations and check procedures; it was written in VB script.

```
Function PenMoth(Julian, Tmean, Tmax, Tmin, Utwo, SoRad, RHmax, RHmin, Lat, Alt)
'
'Penman-Monteith ET equation computation
'Case Rn missing use Hargreaves equation
' PenMoth Macro
' Macro recorded 1/6/2003 by Carlos Wagner Oliveira
'
Dim dr, sigma, ws, Ra, Rso, emm, Rn, Pe, Yui, ea, es, delta, LatHeat As Variant
omg = Application.WorksheetFunction.Pi * Lat / 180
dr = 1 + 0.033 * Cos(2 * Application.WorksheetFunction.Pi * Julian / 365)
sigma = 0.409 * Sin((2 * Application.WorksheetFunction.Pi * Julian / 365) - 1.39)
ws = Application.WorksheetFunction.Acos(-Tan(omg) * Tan(sigma))

Ra = 37.59 * dr * (ws * Sin(omg) * Sin(sigma) + Cos(omg) * Cos(sigma) * Sin(ws))
Rso = (0.75 + 2 * 10 ^ (-5) * Alt) * Ra
''''''
```

A.2 (continued)

```
'Latent heat function of air temp. often used 20C==> 2.45
'LatHeat = (2.501 - (2.361 * 10 ^ (-3)) * Tmean)
LatHeat = 2.45
Yui = 0.00163 * (Pe / LatHeat)
es = ((0.6108 * Exp((17.27 * Tmax) / (Tmax + 237.3))) + (0.6108 * Exp((17.27 * Tmin) /
(Tmin + 237.3)))) / 2
delta = (2504 * Exp((17.27 * Tmean) / (Tmean + 237.3))) / ((Tmean + 237.3) ^ 2)
If Rn = -99999 Or Tmax = -99999 Or Tmin = -99999 Then
   'Case Tmax ot Tmin not available impossible to calculate ET
   PenMoth = -99999
   Else
   PenMoth = (0.408 * delta * (Rn) + Yui * (900 / (Tmean + 273)) * Utwo * (es - ea)) /
(delta + Yui * (1 + 0.34 * Utwo))
End If
'
End Function
```

APPENDIX B

SOIL, COSTS, AND GIS INFORMATION

B.1 Soil series description

Soil series	General description
Chewacla	Series consists of very deep, moderately permeable, somewhat poorly drained soils on flood plains. They formed in recent alluvium washed largely from soils formed in residuum from schist, gneiss, granite, phyllite, and other metamorphic and igneous rocks. Slopes range from 0 to 2 percent. Taxonomic class: Fine-loamy, mixed, active, thermic Fluvaquentic Dystrudepts. Typical pedon: Chewacla loam
Congaree	Series consists of deep, well to moderately well drained, moderately permeable loamy soils that formed in fluvial sediments. Slopes range from 0 to 4 percent. Taxonomic class: Fine-loamy, mixed, active, nonacid, thermic Oxyaquic Udifluvents. Typical pedon: Congaree loam.
State	Series consists of very deep, well-drained, moderate permeability; with slow to medium surface runoff. They formed in loamy fluvial and marine sediments, Slope range from 0 to 10 percent. Taxonomic class: Fine-loamy, mixed, semiactive, thermic Typic Hapludults. Typical pedon: State silt loam.
Toccoa	Series consists of very deep, moderately well drained and well-drained, moderately rapid permeable soils that formed in alluvium. These soils are on flood plains and have slopes that range from 0 to 4 percent. Taxonomic class: Coarse-loamy, mixed, active, nonacid, thermic Typic Udifluvents. Typical pedon: Toccoa sandy loam.
Buncombe	Series consists of very deep, excessively drained sandy soils on nearly level to gently sloping flood plains in the Piedmont and Coastal Plain. They formed in sandy alluvium washed from soils formed in residuum from schist, gneiss, granite, phyllite, and other metamorphic and igneous rocks of the Piedmont. Slopes range from 0 to 6 percent. Taxonomic class: Mixed, thermic Typic Udipsamments. Typical pedon: Buncombe loamy sand.

B.2 Conversions

Grain yields

Some of our traditional terms are more complicated to convert from one system to another. Grain yields for example are conventionally expressed in terms of volume per acre (bu/ac). In the metric system, yield is given by weight (kilograms per hectare).

A yield of 200 bushels per acre is first expressed by weight (200 bu @ 56 lb/bu = 11,200 lbs) and then converted to kilograms (11,200 lbs x .45 kg/lb = 5,040 kg). Since a hectare is equal to about 2.5 acres, it means that 200 bu/ac is equal to about 12,600 kg/ha (5040 kg/ac x 2.5 ac/ha = 12,600 kg/ha). This translates into 126 quintals per hectare and 12.6 metric tons per hectare.

Wheat/soybeans (60# bu)
1 kilogram/hectare (kg/ha) = .0149 (.015) bushels/acre
1 bushel/acre = 67.25 (67) kilograms/hectare

1 quintal/hectare = 1.487 (1.5) bushels/acre
1 bushel/acre = .6725 (.67) quintals/hectare

1 metric ton/hectare = 14.87 (15) bushels/acre
1 bushel/acre = .0673 (.07) metric tons/hectare
Source: http://www.extension.iastate.edu/agdm/wholefarm/html/c6-80.html#grain. Accessed 5 May 2003.

Cwt (abbr. Hundredweight) = a unit of weight in the U.S. Customary System equal to 100 pounds (45.36 kilograms).

A yield of 453.75 cwt per acre is converted to kilograms (45,375 lb x 0.45 kg/lb = 20,582.10 kg). Since a hectare is equal to about 2.5 acres, 453.75 cwt/A is equal to about 51,455.25 kg/ha (20,582.10 kg/A x 2.5 A/ha = 51,455.25 kg/ha). This translates into 51.5 ton/ha.
Source: The American Heritage Dictionary of the English Language, Fourth Edition Copyright © 2000 by Houghton Mifflin Company. Published by Houghton Mifflin Company. Available at: Dictionary.com

B.3 Original crop budget

Source: http://www.utextension.utk.edu/hbin/TomatoBudget.pdf

Staked Tomatoes Drip Irrigated under Plastic (1)

Estimated Returns and Costs per Linear Acre

			Quantity	Units	Price/unit	Total
Income		Tomatoes	1815	25 lb. box	6.00	10890.00
Variable Expenses						
	Plants		3630		0.07	254.10
	Wheat	Cover crop	1.5	bu	6.00	9.00
	Fertilizer	6-12-12	1000	lb	0.09	85.00
	Fertigation	Calcium Nitrate	300	lb	0.20	60.00
		Potassium Nitrate	300	lb	0.23	69.00
		Lime	0.5	ton	16.00	8.00
	Herbicides	Lexone (2)	0.75	lb	19.60	14.70
		Poast 1.5 E.C.	1.5	pts.	8.34	12.51
		Crop Oil Concentrate	1	qt.	2.37	2.37
		Gramoxone Max	0.5	pt.	6.00	3.00
		Non Ionic Surfactant	1	qt	1.94	1.94
	Fungicide (3)	Quadris 2L (4)	24.8	fl oz	2.33	57.78
		Dithane 75DF (5)	14	lbs.	2.70	37.80
		Bravo (6)	3	qts.	12.84	38.52
		Tri-Basic Copper (7)	10	lbs.	1.30	13.00
	Insecticides	Asana XL (8)	48	fl oz	0.88	42.24
		Thiodan (9)	3	qt	10.22	30.66
		Monitor 4 EC (10)	4	pts.	9.87	39.48
		Danitol 2.4EC (11)	14	fl oz	1.16	16.24
	Pkgs, Supplies	Twine	13	balls	5.50	71.50
		Boxes	1815		0.80	1452.00
		Plastic	2	rolls	80.00	160.00
		Drip Tape	1	rolls	130.00	130.00
		Stakes (12)	1900	54"	0.25	118.75
		Picking Buckets (13)	15		6.50	19.50
		Pallets (14)	9		2.50	7.50
	Equipment	Fuel, Oil, & lube	1	ac	38.51	38.51
		Repairs & maintenance	1	ac	32.03	32.03
	Labor	Irrigation Setup	0.67	hrs	8.00	5.36
		Irrigation Maintenance	10.83	hrs	8.00	86.64
		Machinery Operation	1	ac	169.35	169.35
		Picking,Packing, & Grading	1815	box	2.00	3630.00
		Staking	1900	stakes	0.02	38.00
		Tying (5 x @ 0.012)	3630		0.06	217.80
	Irrigation	Fuel	1	ac	25.00	25.00
		Repairs & maintenance	1	ac	10.97	10.97
	Interest	Operating Capital (6 mo.)	3504.13	$	10.0%	350.41
					Total Variable Expenses	7358.67
					Return Above Variable Expenses	3531.33
Fixed Expenses						
	Equipment (15)	Depreciation	1	ac	36.22	36.22
		Interest	1	ac	51.66	51.66
		Housing, Insurance	1	ac	4.95	4.95
	Irrigation (16)	Depreciation	1	ac	76.92	76.92
		Interest	1	ac	18.29	18.29
	Buildings (17)	Depreciation	1	ac	6.56	6.56
		Interest	1	ac	6.56	6.56
		Insurance	1	ac	2.63	2.63
	Land	Rent	1	ac	100.00	100.00
					Total Fixed Expenses	303.79
					Return Above Variable and Fixed Expenses	3227.55

B.3 (continued)

Footnotes
(1) This budget is based on a six foot row spacing resulting in 7260 linear feet per acre. Plants are spaced two feet apart in the row.
(2) Two applications of '1/2 lbs. of Lexone per acre will be made. First application of Lexone will be tank mixed with Poast and Crop oil and sprayed over the entire area. While the second application of Lexone will be tank mixed with Gramoxone and Non ionic surfactant and directed to the bare soil between the plastic.
(3) There will be fourteen application trips of fungicides and insecticides. One every seven days.
(4) Four application trips Quadris at 6.2 fl. oz per acre will be made.
(5) Seven application trips of Dithane at 2 lbs. per acre will be made.
(6) Three applications of Bravo at 1 qt. per acre will be made.
(7) Five applications of Tri-Basic Copper at 2 lbs. per acre will be made.
(8) Five applications of Asana XL at 9.6 oz. per acre will be made.
(9) Three applications of Thiodan at one quart per acre will be made.
(10) Two applications of Monitor 4EC at one quart per acre will be made.
(11) Two applications of Danitol 2.4EC at 7 fl. oz. per acre will be made.
(12) Stakes are assumed to have a life of four years.
(13) Picking buckets are 3/4 bushel hampers with a life of five years.
(14) Pallets are assumed to have a life of three years. (Corrected based on personal communication with the author)
(15) Equipment cost assumes that forty linear acres of tomatoes will be produced. One hundred percent of the cost of the 80 h.p. tractor will be allocated to the tomato enterprise. Thirty-three percent of the cost of the 4-wheel ATV will be allocated to the tomato enterprise. Fifty percent cost of all other equipment will be allocated to the tomato enterprise.
(17) A 20 x 50 building with a cost of $5250 and a life of twenty years is included.
(16) The irrigation equipment is designed for 40 linear acres . Four ten acre blocks are assumed. No cost is included for a water source.

B.3 (continued)

Machinery Cost per Acre
($/acre)

Operation	Times Over	Fuel, Oil and Lube	Repairs & Maint.	Labor	Total Variable Cost	Depr.	Interest	Housing & Insurance	Total Fixed Cost	Total Cost
Plow	1	3.20	0.98	9.90	14.08	1.57	2.75	0.23	4.55	18.63
Disk	5	3.30	1.15	10.10	14.55	2.95	4.20	0.45	7.60	22.15
Fertilize	1	0.95	0.33	2.95	4.23	0.54	0.83	0.11	1.48	5.71
Rotovate	1	3.91	1.45	12.13	17.49	3.81	5.42	0.42	9.65	27.14
Transplant	1	6.92	1.92	55.86	64.70	2.93	4.61	0.45	7.99	72.69
Lay Plastic	1	2.22	0.61	17.88	20.71	0.94	1.48	0.33	2.75	23.46
Boom Spray	1	0.55	0.26	1.72	2.53	1.18	1.69	0.16	3.03	5.56
4-Wheel spray	1	0.70	0.04	5.73	6.47	0.70	1.18	0.19	2.07	8.54
Air-blast spray	14	14.00	22.54	43.40	79.94	11.06	16.52	1.12	28.70	108.64
Lift Plastic	1	0.83	0.23	2.58	3.64	0.35	0.55	0.17	1.07	4.71
Fork Lift	1	1.25	2.25	5.00	8.50	8.33	8.75	1.00	18.08	26.58
Drill Wheat	1	0.68	0.27	2.10	3.05	1.86	3.68	0.32	5.86	8.91
Total		38.51	32.03	169.35	239.89	36.22	51.66	4.95	92.83	332.72

Irrigation System Cost Per Acre

Description	Price	Life (yrs)	$/acre Fuel	Repairs	Depreciati	Interest
Pump 25HP	3200	7	25.00	2.40	11.43	4.00
Sand Filters (Stainless Steel)	4000	20		3.00	5.00	5.00
Connections	300	3		0.23	2.50	0.38
4" Lay Flat Tube - 5,200 ft (widt	6600	3		4.95	55.00	8.25
Blue Lay Flat - 300 ft.	230	3		0.17	1.92	0.29
Fert. Injector	300	7		0.23	1.07	0.38
Total			25.00	10.97	76.92	18.29

B.4 Modified crop budget

Staked Tomatoes Drip Irigated under Plastic

		Quantity	Unit	Price/unit	Total
Income Tomatoes		1815	25lb. Box	6	10890
Variable Expenses					
	Plants	3630		0.07	254.1
Wheat	Cover crop	1.5	bu	6	9
Fertilizer	6/12/12	1000	lb	0.09	85
Fertigation	Calcium Nitrate	300	lb	0.2	60
	Potassium Nitrate	300	lb	0.23	69
	Lime	0.5	ton	16	8
Herbicides	Lexone (2)	0.75	lb	19.6	14.7
	Poast 1.5 E.C.	1.5	pts.	8.34	12.51
	Crop Oil Concetrate	1	qt.	2.37	2.37
	Gramoxone Max	0.5	pt.	6	3
	Non Ionic Surfactant	1	qt	1.94	1.94
Fungicide (	Quadris 2L (4)	24.8	fl oz	2.33	57.78
	Dithane 75DF (5)	14	lbs.	2.7	37.8
	Bravo (6)	3	qts.	12.84	38.52
	Tri-Basic Copper (7)	10	lbs.	1.3	13
Insecticides	Asana XL (8)	48	fl oz	0.88	42.24
	Thiodan (9)	3	qt	10.22	30.66
	Monitor 4 EC (10)	4	pts.	9.87	39.48
	Danitol 2.4EC (11)	14	fl oz	1.16	16.24
Pkgs, Supp	Twine	13	balls	5.5	71.5
	Boxes	1815		0.8	1452
	Plastic	2	rolls	80	160
	Stakes (12)	1900	54"	0.25	118.75
	Picking Buckets (13)	15		6.5	19.5
	Pallets (14)	9		2.5	7.5
Equipment	Fuel, Oil, & lube	1	ac	38.51	38.51
Labor	Repairs & maintenance	1	ac	32.03	32.03
	Machinery Operation	1	ac	169.35	169.35
	Staking	1900	stakes	0.02	38
	Tying (5 x @ 0.012)	3630		0.06	217.8
Interest	Operating Capital (6 mo.)	1560.14	$	10.00%	156.01
Total Variable Expenses					3276.29
Return Above Variable Expenses					7613.71
Fixed Expenses					
	Equipment Depreciation	1	ac	36.22	36.22
	Interest	1	ac	51.66	51.66
	Housing, Insurance	1	ac	4.95	4.95
	Buildings (: Depreciation	1	ac	6.56	6.56
	Interest	1	ac	6.56	6.56
	Insurance	1	ac	2.63	2.63
	Land Rent	1	ac	100	100
Total Fixed Expenses					208.58
Return Above Variable and Fixed Expenses					7405.13
Total Annual Costs					3484.87

B.4 (continued)

Variable Expenses/Irrigation					
Pkgs, Supp	Drip Tape	1	rolls	130	130
Labor	Irrigation Maintenance	10.83	hrs	8	86.64
Irrigation	Repairs & maintenance	1	ac	6.83	6.825
Interest	Operating Capital (6 mo.)	111.73	$	10.00%	11.17
Total Variable Expenses					234.64
Fixed Irrigation Cost					
	Irrigation (1 Depreciation	1	ac	21.92	21.91865
	Interest	1	ac	11.38	11.375
Total Fixed Expenses					33.29365
Total Annual Costs Irrigation					267.93
Overall Total Annual Cost					3752.81

Irrigation system cost per acre				$/acre		
	Price	Life	Repairs	Depreciation	Interest	Total
Pump 25HP	3200	9	2.40	8.89	4.00	15.29
Sand Filters	4900	20	3.68	6.13	6.13	15.93
Connections	300	3	0.23	2.50	0.38	3.10
Blue Lay Falt - 6" x 300ft	400	3	0.30	3.33	0.50	4.13
Fert. Injector	300	7	0.23	1.07	0.38	1.67
Total	9100		6.83	21.92	11.38	40.12

B.5 Procedure to individualize areas.

This procedure is intended to individualize sub-areas that occur at different locations within the field with the same AWHC and that are considered as one unit. It was used in ArcMap 8.1.

1. Choose layer (shape file)
   1.1. Select the field that contains either soil type or soil legends
2. Convert original shapefile into raster
   2.1 Use spatial analyst ➔ convert ➔ features to raster
3. Convert the raster back to shapefile
   3.1 Spatial analyst ➔ converts ➔ raster to features (choose default field)
   Note: At this point should have a map similar to the original but with more records representing the individual management unit. Still need to reassign values.
4. On ArcCatalog create new shapefile as points
   Note: Select same projection as the files to combine
5. Add the new point shapefile to the table of contents
6. Edit the point shapefile
   6.1 Use editor toolbar
   6.2 Draw a point to each polygon
   6.3 Save the edit
   6.4 Stop editing
   Note: Should have one point for each polygon in the points attribute table.
7. Join original shapefile to point (select first points layer)
   7.1 Right click on points layer
   7.2 Join data from another layer based on spatial location
   7.3 Choose original layer that contains labels of soil type
   7.4. You are joining polygons to points that fall inside
   7.5 Name the Output file
8. Join the output file from previous step to the shapefile (created in step 3)
   8.1 Right click on shapefile created in step 3
   8.2 Join data from another layer based on spatial location
   8.3 Choose the layer to join as the output layer from step 7
   8.4 You are joining polygons to polygons, each polygon will be given the attributes of the polygon it falls completely inside of the layer being joined.
   8.2 Name the Output file
9. Remove the files that are not needed but were used for the process, eliminate unnecessary fields in the attribute table of the new layer.

B.6 Attribute table with calculated AWHC used on the site-specific irrigation schedule

FID	ID	SOIL_SERIE	SURFACE_TE	SOIL_TYPE	SLOPE	MAPPING_UN
0	0	Chewacla	Sandy Loam	Chewacla Sandy Loam	0-3%	Chewacla Sandy Loam, 0-3%
1	1	Congaree	Sandy Loam	Congaree Sandy Loam	0-3%	Congaree Sandy Loam, 0-3%
2	2	State	Fine Sandy Loam	State Fine Sandy Loam	0-3%	State Fine Sandy Loam, 0-3%
3	3	Buncombe	Loamy Sand	Buncombe Loamy Sand	0-3%	Buncombe Loamy Sand, 0-3%
4	4	Toccoa	Sandy Loam/Loamy Sand	Toccoa Sandy Loam/Loamy Sand	0-3%	Toccoa Sandy Loam/Loamy Sand, 0-3%
5	5	Congaree	Sandy Loam	Congaree Sandy Loam	0-3%	Congaree Sandy Loam, 0-3%

(continued)

ABBREVIATI	CENT_X	CENT_Y	AREA_M2	Lay_W_1	Lay_W_2	Lay_W_3	Lay_W_4	Lay_W_5	Lay_W_6
ChA	854812.5	188235.1	2967.608	225.74	185.61	180.03	177.81	159.84	131.68
CoA	854860	188138.8	14988.73	177.67	185.61	180.03	177.81	159.84	131.68
StA	854795.3	188079.9	22133.09	171.75	171.75	171.75	177.81	159.84	131.68
BuA	854976	188306.3	41641.82	50	50	50	50	50	131.68
ToA	854908.4	188335.8	38194.19	121	121	121	121	159.84	131.68
CoA	854779.8	188476.3	42475.32	177.67	177.67	180.03	177.81	159.84	131.68

APPENDIX C

ADDITIONAL RESULTS INFORMATION

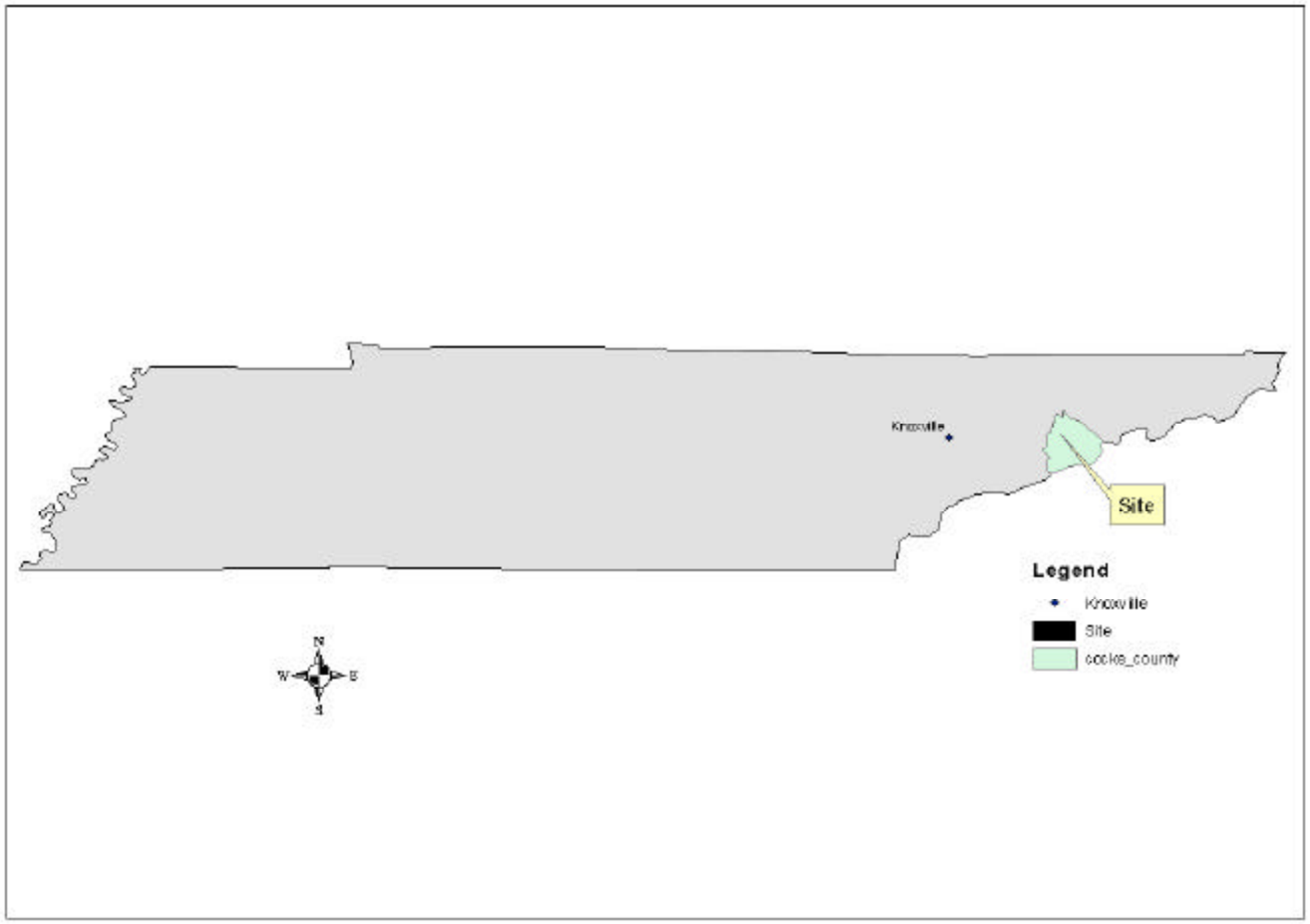


Figure C.1. Tennessee state map indicating site location.

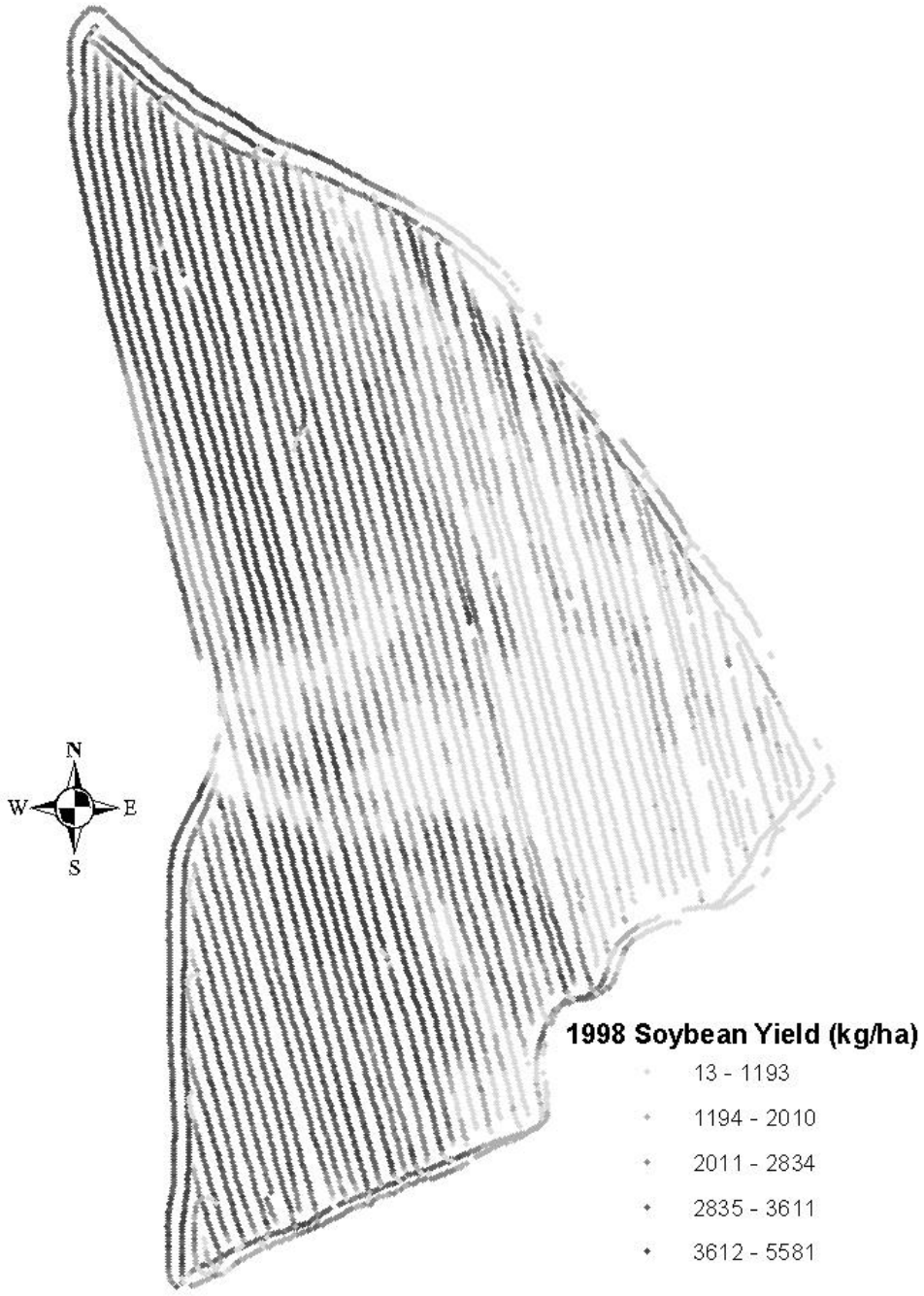


Figure C.2. Corrected 1998 yield data positions for field in Cocke County.

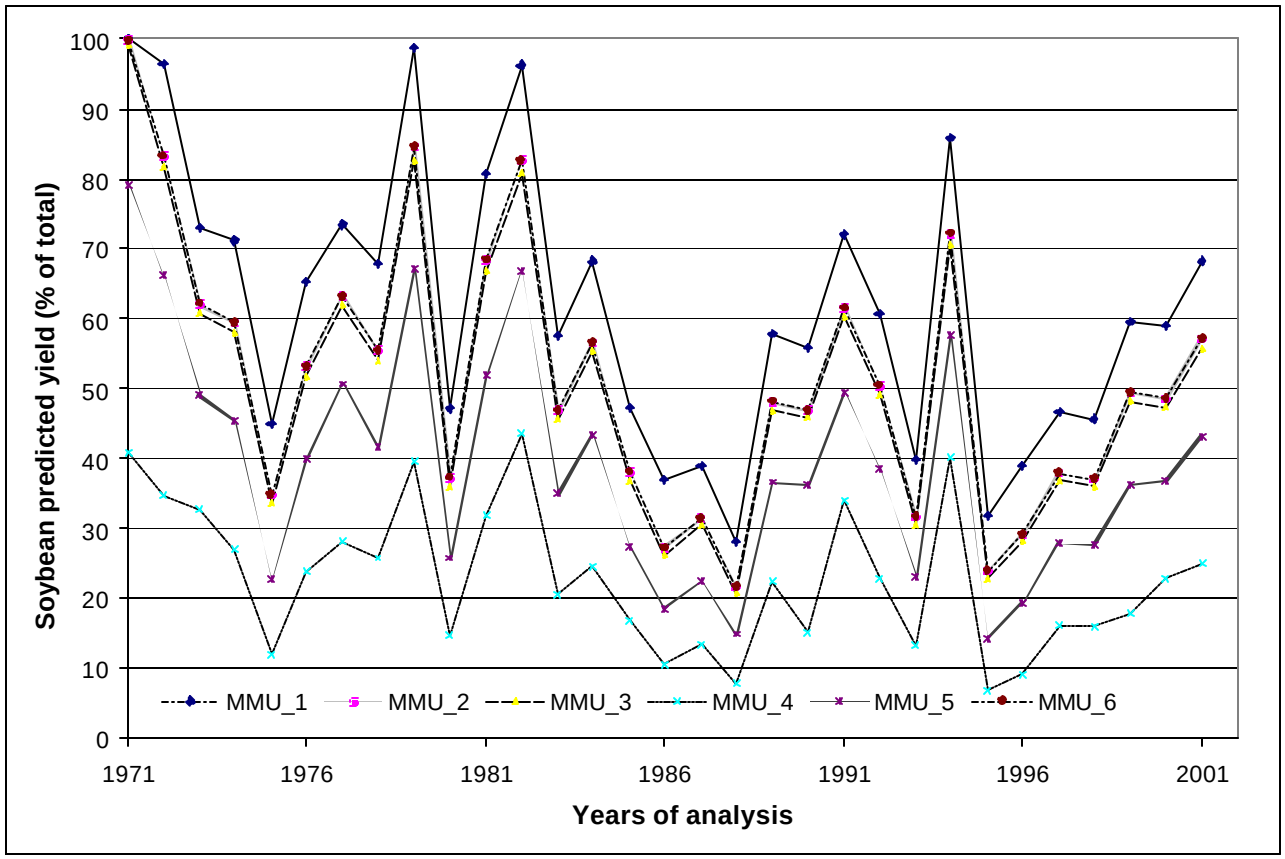


Figure C.3. Estimated soybean yield as percentage of total yield for field in Cocke County considering several irrigation management layouts, using evapotranspiration and precipitation data from Knoxville McGhee Tyson Airport weather station.

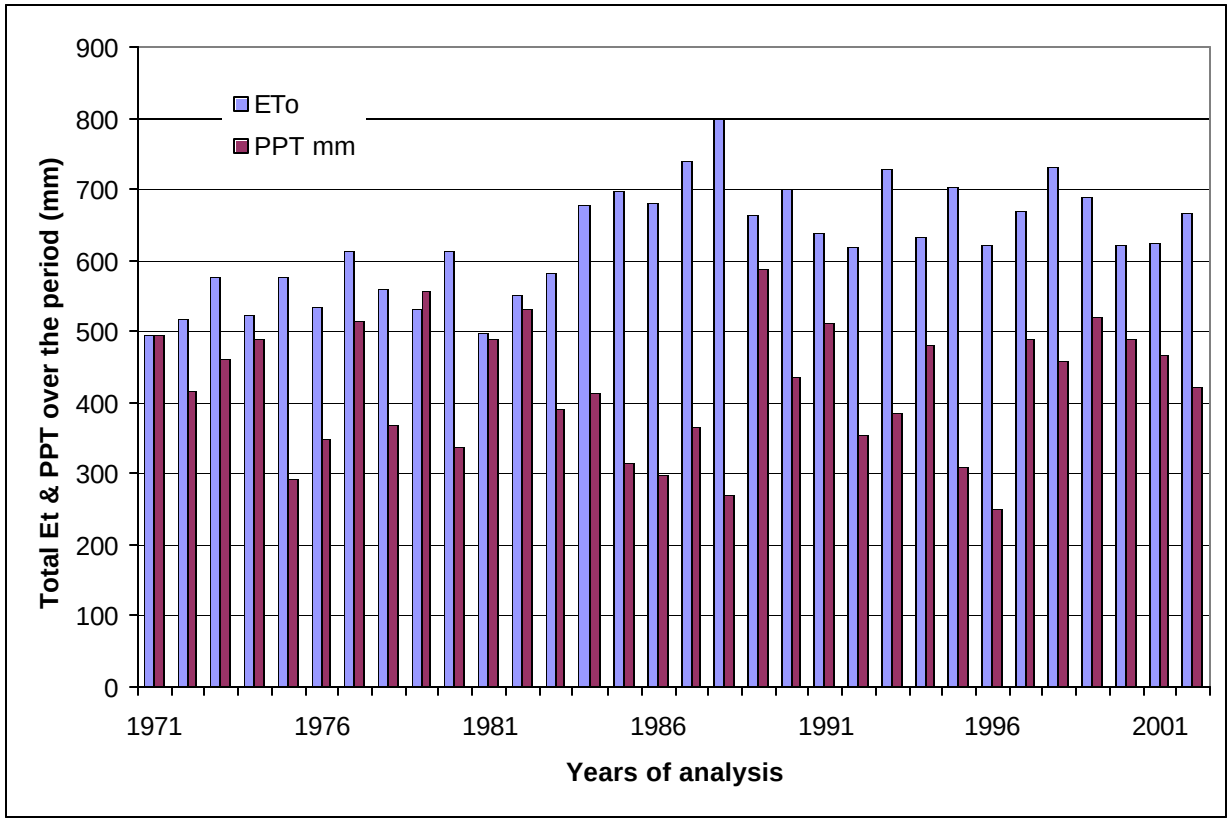


Figure C.4. Cumulative evapotranspiration and precipitation over the period of soybean growth May15 to September 26 over the 31 years of data, Knoxville McGhee Tyson Airport weather station.

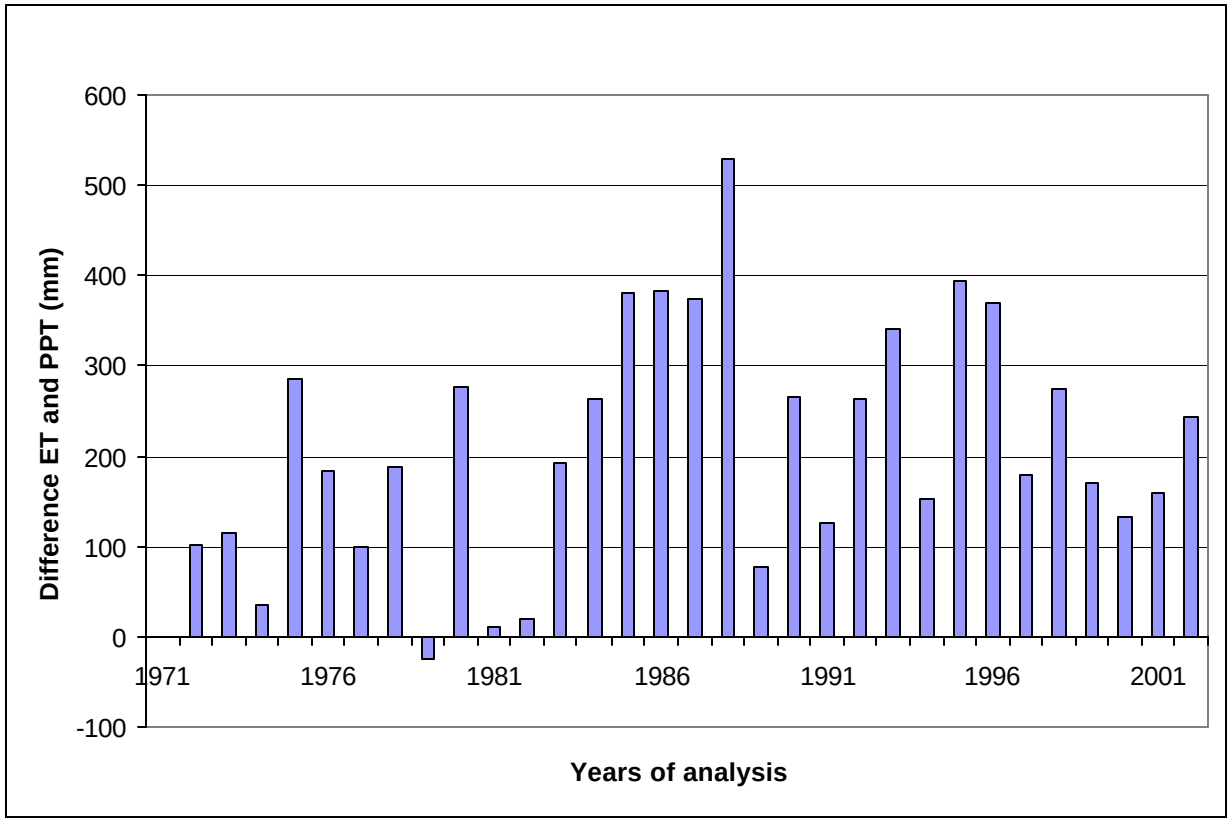


Figure C.5. Difference in cumulative evapotranspiration and precipitation over the period of soybean growth May15 to September 26 over the 31 years of data, Knoxville McGhee Tyson Airport weather station.

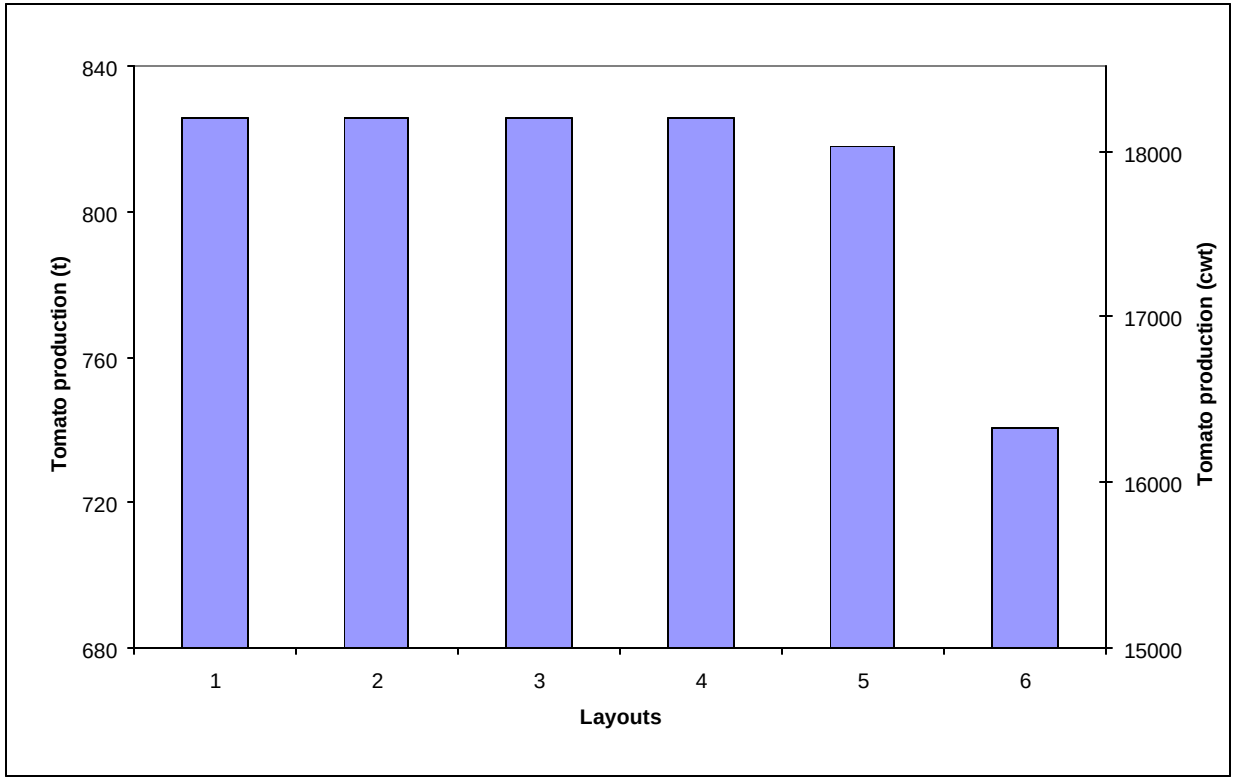


Figure C.6. Average annual tomato production for the various layouts over the 31 years of analysis (1971 to 2001).

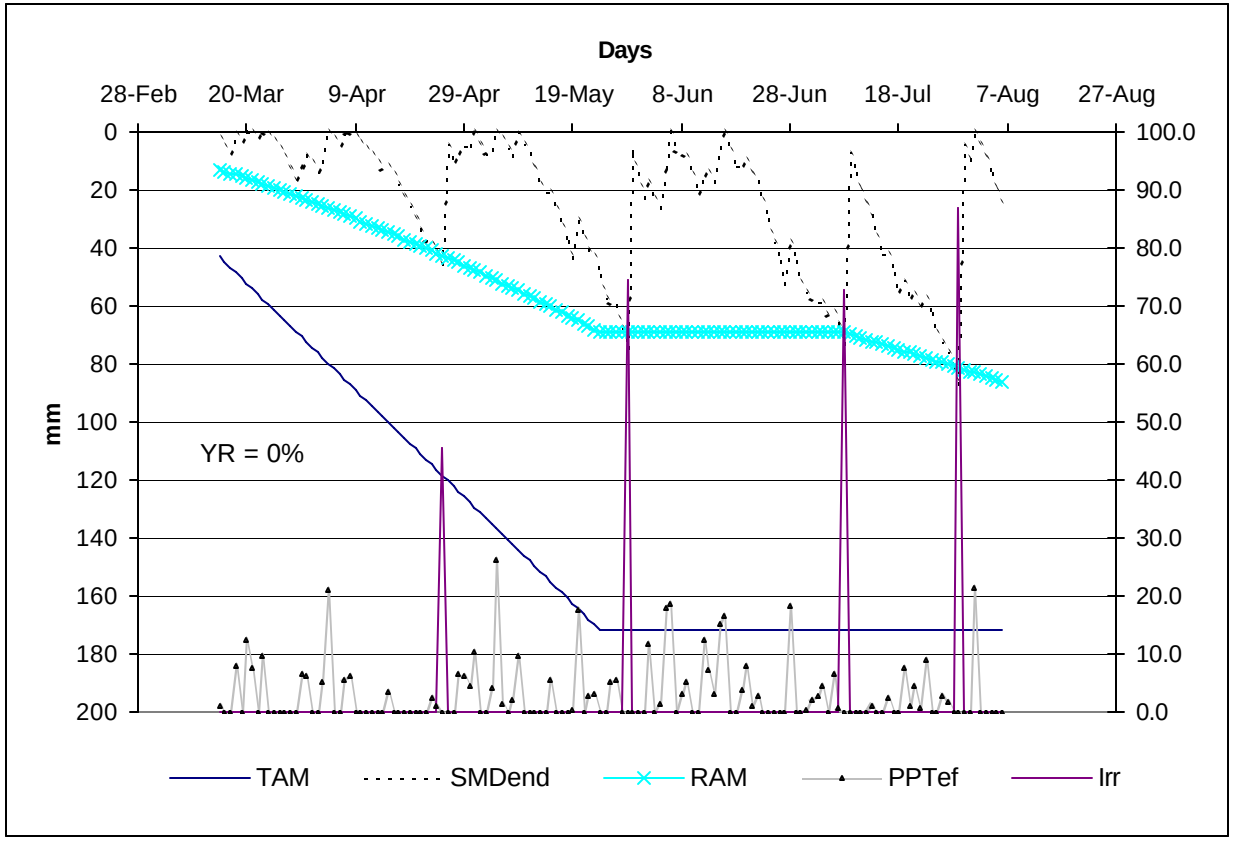


Figure C.7. Soil water balance for MMU_3 under layout 4 (1989). The irrigation water applied for tomatoes was 279.6 mm, with no yield reduction for this year.

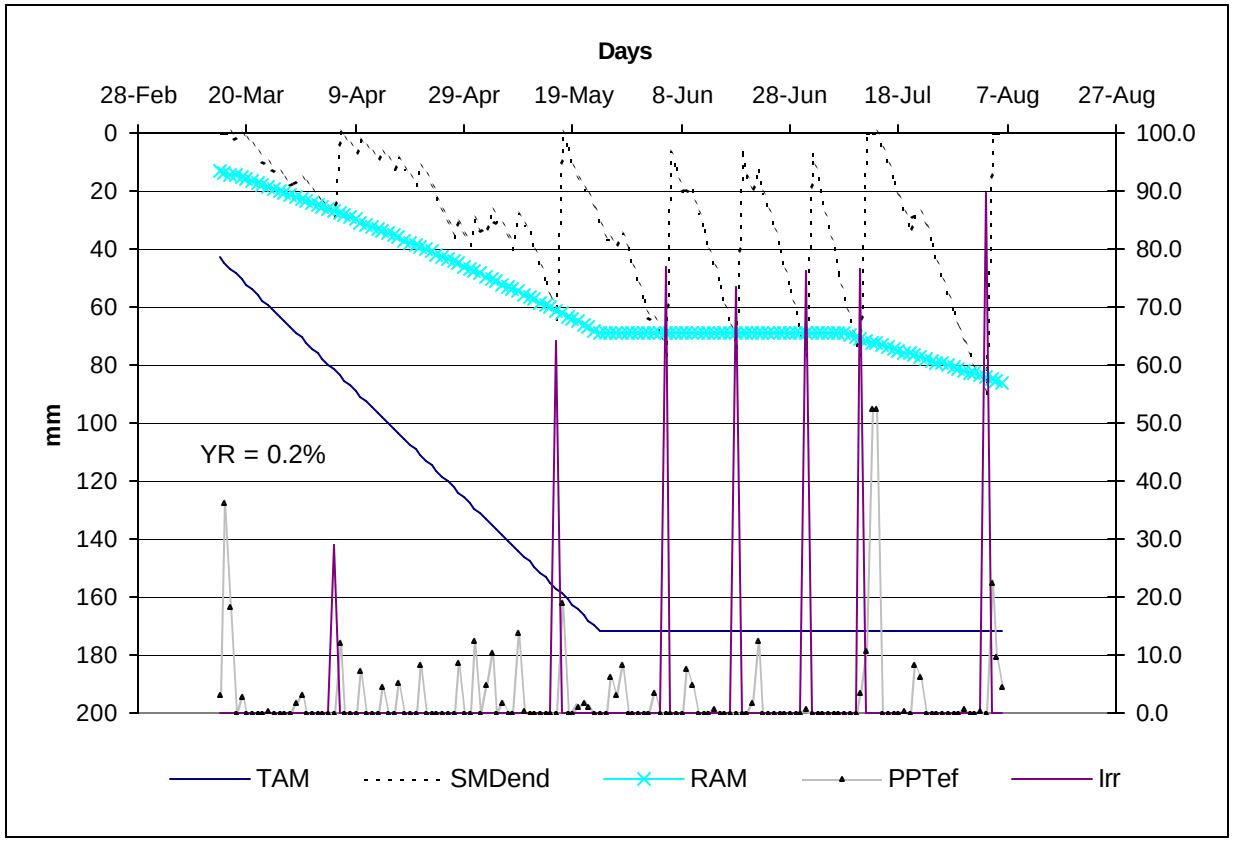


Figure C.8. Soil water balance for MMU_3 under layout 4 (1990). The irrigation water applied was 486.4 mm and there was high yield reduction this year, with a water loss of 0.4 mm.

APPENDIX D

DESCRIPTIVE STATISTICS

Table D.1. Water applied to the field in thousands of cubic meters.

Year	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
1971	30.02	30.08	29.90	29.90	34.45	26.85
1972	31.40	31.66	31.56	31.76	36.11	36.83
1973	29.02	29.48	29.18	29.31	26.91	28.95
1974	31.54	31.90	32.03	31.83	28.16	34.31
1975	60.65	59.67	60.91	61.25	56.22	52.49
1976	41.16	41.10	41.53	41.43	43.94	50.08
1977	61.45	60.66	61.99	61.99	62.16	58.88
1978	42.19	42.55	42.30	42.42	37.69	40.08
1979	26.20	26.59	26.67	26.32	24.28	23.88
1980	55.14	55.11	55.16	53.54	57.75	53.11
1981	37.43	37.71	37.53	37.64	43.45	34.73
1982	34.34	34.30	34.19	34.32	44.61	34.45
1983	42.68	43.17	42.77	42.89	37.52	47.23
1984	43.68	44.03	44.65	43.77	48.46	44.61
1985	71.52	70.67	72.66	73.23	70.71	73.62
1986	87.38	87.96	88.70	88.59	88.85	93.71
1987	61.97	62.50	63.62	61.90	65.51	60.00
1988	100.08	100.48	100.19	99.83	103.55	99.97
1989	50.04	50.67	50.31	50.43	45.19	43.18
1990	74.31	72.35	70.57	75.20	70.43	62.96
1991	54.56	53.19	49.40	54.94	50.39	44.69
1992	58.61	59.44	59.16	59.04	62.95	57.85
1993	76.83	77.07	76.84	75.16	78.96	78.13
1994	48.08	48.50	48.16	48.64	49.64	43.15
1995	68.18	68.60	68.69	66.64	67.01	70.55
1996	63.40	63.63	63.78	63.60	60.07	63.02
1997	42.65	42.75	42.75	42.99	40.02	38.27
1998	48.21	48.13	48.03	46.52	47.44	58.10
1999	51.80	52.20	52.27	52.19	55.58	53.07
2000	42.21	42.44	42.30	42.40	38.03	34.45
2001	60.07	60.42	60.35	60.42	55.03	61.93

Statistics	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
Average	52.48	52.55	52.52	52.58	52.62	51.71
STDEV	17.76	17.65	17.77	17.77	18.03	18.34
Max	100.08	100.48	100.19	99.83	103.55	99.97
Min	26.20	26.59	26.67	26.32	24.28	23.88
Total	1626.79	1629.02	1628.15	1630.11	1631.09	1603.11

Table D. 2. Predicted tomato yield (metric ton) based on a maximum of 50.85 ton/ha (453.75 cwt/acre) for the different field irrigation management layouts, over the years of analysis (1971 to 2001).

Year	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
1971	825.96	825.87	825.96	825.96	819.22	745.49
1972	825.96	825.93	825.96	825.95	821.21	751.60
1973	825.96	825.83	825.96	825.96	822.16	757.91
1974	825.96	825.91	825.94	825.95	820.56	761.13
1975	825.96	825.87	825.96	825.89	817.57	727.88
1976	825.96	825.96	825.95	825.87	816.59	726.73
1977	825.96	825.86	825.96	825.89	817.20	733.17
1978	825.96	825.88	825.96	825.94	819.61	740.03
1979	825.96	825.94	825.92	825.96	822.38	771.06
1980	825.96	825.92	825.96	825.88	812.03	737.06
1981	825.96	825.87	825.96	825.91	817.25	745.13
1982	825.96	825.91	825.96	825.88	816.29	760.46
1983	825.96	825.86	825.96	825.96	818.50	737.80
1984	825.96	825.96	825.95	825.96	820.41	751.78
1985	825.96	825.88	825.96	825.89	815.80	722.07
1986	825.96	825.88	825.96	825.82	814.05	716.44
1987	825.96	825.95	825.91	825.96	818.22	733.50
1988	825.96	825.93	825.96	825.93	814.30	721.62
1989	825.96	825.87	825.96	825.96	815.52	745.36
1990	825.96	825.89	825.96	825.77	817.17	736.28
1991	825.96	825.91	825.96	825.86	815.86	742.32
1992	825.96	825.84	825.95	825.94	815.76	734.22
1993	825.96	825.91	825.95	825.84	815.25	731.26
1994	825.96	825.80	825.96	825.83	820.08	751.33
1995	825.96	825.93	825.96	825.89	816.06	723.55
1996	825.96	825.92	825.95	825.86	819.27	742.60
1997	825.96	825.96	825.96	825.88	819.02	747.50
1998	825.96	825.93	825.96	825.91	818.84	749.41
1999	825.96	825.88	825.87	825.87	817.15	743.73
2000	825.96	825.89	825.96	825.90	822.51	746.98
2001	825.96	825.80	825.96	825.86	818.53	728.20

Statistics	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
Average	825.96	825.89	825.95	825.90	817.88	740.76
STDEV	0.00	0.04	0.02	0.05	2.55	12.93
Max	825.96	825.96	825.96	825.96	822.51	771.06
Min	825.96	825.80	825.87	825.77	812.03	716.44
Total	25604.73	25602.72	25604.50	25602.91	25354.36	22963.55

Table D.3. Predicted yield as a percentage of the maximum yield for MMU_4 for the different field irrigation management layouts.

Year	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
1971	100.0	100.0	100.0	100.0	100.0	62.4
1972	100.0	100.0	100.0	100.0	100.0	65.2
1973	100.0	100.0	100.0	100.0	100.0	68.3
1974	100.0	100.0	100.0	100.0	100.0	69.7
1975	100.0	100.0	100.0	100.0	100.0	54.1
1976	100.0	100.0	100.0	100.0	100.0	53.6
1977	100.0	100.0	100.0	100.0	100.0	56.6
1978	100.0	100.0	100.0	100.0	100.0	59.6
1979	100.0	100.0	100.0	100.0	100.0	74.2
1980	100.0	100.0	100.0	100.0	100.0	58.3
1981	100.0	100.0	100.0	100.0	100.0	62.0
1982	100.0	100.0	100.0	100.0	100.0	69.3
1983	100.0	100.0	100.0	100.0	100.0	58.7
1984	100.0	100.0	100.0	100.0	100.0	65.1
1985	100.0	100.0	100.0	100.0	100.0	51.3
1986	100.0	100.0	100.0	100.0	100.0	48.9
1987	100.0	100.0	100.0	100.0	100.0	56.6
1988	100.0	100.0	100.0	100.0	100.0	51.1
1989	100.0	100.0	100.0	100.0	100.0	62.2
1990	100.0	100.0	100.0	100.0	100.0	57.8
1991	100.0	100.0	100.0	100.0	100.0	60.8
1992	100.0	100.0	100.0	100.0	100.0	57.0
1993	100.0	100.0	100.0	100.0	100.0	55.5
1994	100.0	100.0	100.0	100.0	100.0	65.0
1995	100.0	100.0	100.0	100.0	100.0	52.2
1996	100.0	100.0	100.0	100.0	100.0	60.9
1997	100.0	100.0	100.0	100.0	100.0	63.4
1998	100.0	100.0	100.0	100.0	100.0	64.3
1999	100.0	100.0	100.0	100.0	100.0	61.3
2000	100.0	100.0	100.0	100.0	100.0	62.8
2001	100.0	100.0	100.0	100.0	100.0	54.4

Table D.4. Gross income based on price and yield for each year as predicted by the SSIS over the 31 years of analysis (thousands of dollars).

Year	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
1971	589.47	589.40	589.47	589.47	584.66	532.04
1972	549.92	549.90	549.92	549.91	546.76	500.41
1973	843.20	843.07	843.20	843.20	839.32	773.73
1974	691.76	691.71	691.74	691.75	687.24	637.46
1975	836.57	836.48	836.57	836.50	828.07	737.22
1976	463.58	463.57	463.57	463.52	458.31	407.88
1977	856.59	856.48	856.59	856.51	847.51	760.35
1978	806.60	806.52	806.60	806.58	800.40	722.68
1979	679.18	679.16	679.15	679.18	676.23	634.04
1980	604.15	604.13	604.15	604.09	593.97	539.13
1981	556.44	556.38	556.44	556.41	550.57	501.99
1982	590.38	590.35	590.38	590.33	583.47	543.56
1983	495.42	495.36	495.42	495.42	490.95	442.54
1984	556.89	556.89	556.88	556.89	553.14	506.87
1985	477.08	477.03	477.07	477.03	471.21	417.07
1986	518.56	518.51	518.56	518.47	511.08	449.80
1987	522.51	522.50	522.48	522.51	517.61	464.02
1988	642.22	642.20	642.22	642.19	633.15	561.09
1989	578.97	578.91	578.97	578.97	571.66	522.47
1990	561.26	561.22	561.26	561.13	555.29	500.32
1991	500.93	500.90	500.93	500.87	494.81	450.20
1992	451.29	451.22	451.28	451.28	445.71	401.17
1993	555.22	555.18	555.21	555.14	548.02	491.56
1994	590.87	590.76	590.87	590.78	586.67	537.48
1995	413.99	413.97	413.99	413.96	409.03	362.66
1996	515.76	515.73	515.75	515.70	511.58	463.70
1997	545.81	545.81	545.81	545.75	541.22	493.96
1998	736.95	736.92	736.95	736.90	730.59	668.64
1999	628.87	628.81	628.81	628.81	622.17	566.26
2000	601.19	601.14	601.19	601.15	598.68	543.70
2001	364.18	364.11	364.18	364.14	360.90	321.08

Statistics	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
Average	591.15	591.11	591.15	591.11	585.48	530.81
STDEV	123.46	123.44	123.46	123.46	122.88	113.71
Max	856.59	856.48	856.59	856.51	847.51	773.73
Min	364.18	364.11	364.18	364.14	360.90	321.08
Total	18325.79	18324.34	18325.63	18324.55	18149.99	16455.10

Table D.5. Cost of fuel and lubricant (Dollars) for the different irrigation management layouts assuming a price of $0.396/l ($1.50/gal).

Year	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
1971	1365	1498	1490	1490	1716	1338
1972	1564	1577	1572	1582	1799	1835
1973	1446	1469	1454	1460	1341	1442
1974	1572	1589	1596	1586	1403	1709
1975	3021	2973	3034	3051	2801	2615
1976	2051	2048	2069	2064	2189	2495
1977	3062	3022	3088	3088	3097	2933
1978	2102	2120	2107	2113	1878	1997
1979	1305	1325	1329	1311	1210	1190
1980	2747	2746	2748	2667	2877	2646
1981	1865	1879	1870	1875	2164	1730
1982	1711	1709	1703	1710	2222	1716
1983	2126	2150	2131	2137	1869	2353
1984	2176	2194	2224	2181	2414	2222
1985	3563	3521	3620	3648	3523	3668
1986	4353	4382	4419	4413	4427	4668
1987	3087	3114	3169	3084	3264	2989
1988	4986	5006	4991	4973	5159	4980
1989	2493	2525	2507	2513	2251	2151
1990	3702	3604	3516	3746	3509	3136
1991	2718	2650	2461	2737	2511	2226
1992	2920	2961	2947	2941	3136	2882
1993	3828	3839	3828	3745	3934	3892
1994	2395	2416	2399	2423	2473	2150
1995	3397	3418	3422	3320	3338	3515
1996	3159	3170	3177	3169	2993	3139
1997	2125	2130	2130	2142	1994	1907
1998	2402	2398	2393	2318	2363	2895
1999	2580	2600	2604	2600	2769	2644
2000	2103	2114	2107	2112	1894	1716
2001	2993	3010	3006	3010	2742	3085

Statistics	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
Average	2610	2618	2617	2620	2621	2576
STDEV	891	879	885	885	898	914
Max	4986	5006	4991	4973	5159	4980
Min	1305	1325	1329	1311	1210	1190
Total	80915	81156	81112	81210	81259	79865

Table D.6. Predicted harvest cost in thousands of dollars for the different irrigation management layouts over the 31 years of data with a fixed labor cost of $0.176/kg ($0.08/lb).

Year	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
1971	152.96	152.94	152.96	152.96	151.71	138.05
1972	152.96	152.95	152.96	152.95	152.08	139.19
1973	152.96	152.93	152.96	152.96	152.25	140.35
1974	152.96	152.95	152.95	152.95	151.96	140.95
1975	152.96	152.94	152.96	152.94	151.40	134.79
1976	152.96	152.95	152.95	152.94	151.22	134.58
1977	152.96	152.94	152.96	152.94	151.33	135.77
1978	152.96	152.94	152.96	152.95	151.78	137.04
1979	152.96	152.95	152.95	152.96	152.29	142.79
1980	152.96	152.95	152.96	152.94	150.38	136.49
1981	152.96	152.94	152.96	152.95	151.34	137.99
1982	152.96	152.95	152.96	152.94	151.17	140.83
1983	152.96	152.94	152.96	152.96	151.57	136.63
1984	152.96	152.95	152.95	152.96	151.93	139.22
1985	152.96	152.94	152.96	152.94	151.07	133.72
1986	152.96	152.94	152.96	152.93	150.75	132.67
1987	152.96	152.95	152.95	152.96	151.52	135.83
1988	152.96	152.95	152.96	152.95	150.80	133.63
1989	152.96	152.94	152.96	152.96	151.02	138.03
1990	152.96	152.94	152.96	152.92	151.33	136.35
1991	152.96	152.95	152.96	152.94	151.09	137.47
1992	152.96	152.93	152.95	152.95	151.07	135.97
1993	152.96	152.95	152.95	152.93	150.97	135.42
1994	152.96	152.93	152.96	152.93	151.87	139.13
1995	152.96	152.95	152.96	152.94	151.12	133.99
1996	152.96	152.95	152.95	152.94	151.72	137.52
1997	152.96	152.96	152.96	152.94	151.67	138.43
1998	152.96	152.95	152.96	152.95	151.64	138.78
1999	152.96	152.94	152.94	152.94	151.32	137.73
2000	152.96	152.94	152.96	152.94	152.32	138.33
2001	152.96	152.93	152.96	152.94	151.58	134.85

Statistics	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
Average	152.96	152.94	152.95	152.94	151.46	137.18
STDEV	0.00	0.01	0.00	0.01	0.47	2.39
Max	152.96	152.96	152.96	152.96	152.32	142.79
Min	152.96	152.93	152.94	152.92	150.38	132.67
Total	4741.62	4741.24	4741.57	4741.28	4695.25	4252.51

Table D.7. Expected net return for the field for the various irrigation management units over the 31 years of analysis (thousands of dollars).

Year	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
1971	280.91	281.05	281.43	281.76	278.29	240.03
1972	241.16	241.46	241.80	242.11	239.94	206.77
1973	534.56	534.75	535.20	535.52	532.78	479.31
1974	382.99	383.27	383.60	383.95	380.93	342.18
1975	526.35	526.65	526.99	527.24	520.92	447.19
1976	154.33	154.66	154.96	155.25	151.96	118.18
1977	546.33	546.61	546.95	547.21	540.13	469.03
1978	497.30	497.54	497.94	498.25	493.79	431.02
1979	370.68	370.97	371.28	371.65	369.79	337.44
1980	294.21	294.52	294.86	295.22	287.77	247.37
1981	247.38	247.65	248.03	248.32	244.12	209.65
1982	281.48	281.78	282.13	282.41	277.14	248.40
1983	186.11	186.36	186.75	187.06	184.56	150.94
1984	247.52	247.82	248.11	248.48	245.86	212.81
1985	166.32	166.65	166.91	167.17	163.67	127.06
1986	207.01	207.27	207.59	207.86	202.96	159.83
1987	212.23	212.52	212.77	213.20	209.88	172.57
1988	330.04	330.33	330.68	331.00	324.25	269.85
1989	269.29	269.54	269.92	270.24	265.44	229.67
1990	250.37	250.76	251.20	251.20	247.51	208.22
1991	191.02	191.39	191.92	191.93	188.26	157.89
1992	141.18	141.41	141.79	142.11	138.57	109.69
1993	244.20	244.48	244.84	245.19	240.17	199.63
1994	281.29	281.50	281.93	282.16	279.38	243.58
1995	103.40	103.69	104.02	104.43	101.62	72.53
1996	205.41	205.70	206.03	206.32	203.93	170.42
1997	236.49	236.81	237.13	237.40	234.61	201.00
1998	427.35	427.66	428.01	428.37	423.65	374.35
1999	319.10	319.36	319.67	320.00	315.13	273.27
2000	291.90	292.17	292.54	292.83	291.52	251.04
2001	53.99	54.26	54.63	54.92	53.64	30.52

Statistics	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
Average	281.35	281.63	281.99	282.28	278.46	238.43
STDEV	123.66	123.65	123.66	123.66	122.97	113.04
Max	546.33	546.61	546.95	547.21	540.13	479.31
Min	53.99	54.26	54.63	54.92	53.64	30.52
Total	8721.92	8730.61	8741.62	8750.75	8632.18	7391.44

Table D.8. Expected net return for MMU_4 for the different irrigation management units over the 31 years of analysis (thousands of dollars).

Year	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
1971	71.96	71.98	72.04	72.11	72.17	30.32
1972	61.69	61.76	61.82	61.89	61.95	26.68
1973	136.93	137.00	137.06	137.13	137.19	81.38
1974	98.08	98.14	98.21	98.27	98.34	56.62
1975	134.92	134.99	135.05	135.11	135.18	54.96
1976	39.40	39.47	39.53	39.60	39.66	2.85
1977	140.05	140.12	140.18	140.24	140.31	62.09
1978	127.42	127.49	127.55	127.62	127.68	60.20
1979	94.91	94.98	95.04	95.11	95.17	60.61
1980	75.35	75.42	75.48	75.55	75.61	27.60
1981	63.39	63.46	63.52	63.58	63.65	24.56
1982	72.02	72.09	72.15	72.22	72.28	38.06
1983	47.67	47.73	47.80	47.86	47.92	11.74
1984	63.24	63.31	63.37	63.44	63.50	27.62
1985	42.57	42.63	42.69	42.76	42.82	2.50
1986	52.98	53.05	53.11	53.17	53.24	5.42
1987	54.28	54.35	54.41	54.48	54.54	13.64
1988	84.57	84.64	84.70	84.77	84.83	23.70
1989	68.97	69.03	69.09	69.16	69.22	28.26
1990	64.23	64.30	64.36	64.43	64.49	20.57
1991	48.89	48.95	49.02	49.08	49.15	14.50
1992	36.14	36.21	36.27	36.34	36.40	3.66
1993	62.53	62.60	62.66	62.73	62.79	17.07
1994	72.13	72.19	72.26	72.32	72.38	33.22
1995	26.41	26.48	26.54	26.61	26.67	-5.18
1996	52.56	52.62	52.68	52.75	52.81	16.65
1997	60.43	60.49	60.56	60.62	60.68	24.21
1998	109.48	109.54	109.60	109.67	109.73	56.29
1999	81.65	81.71	81.78	81.84	81.91	34.98
2000	74.66	74.72	74.79	74.85	74.92	32.53
2001	13.74	13.80	13.87	13.93	14.00	-10.51

Statistics	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
Average	72.04	72.10	72.17	72.23	72.30	28.28
STDEV	31.71	31.71	31.71	31.71	31.71	22.08
Max	140.05	140.12	140.18	140.24	140.31	81.38
Min	13.74	13.80	13.87	13.93	14.00	-10.51
Total	2233.27	2235.22	2237.21	2239.21	2241.20	876.77

Table D.9. Expected net return for the field for the various irrigation management units over the 31 years of analysis (thousands of dollars) considering a minimum tomato price of $20/cwt.

Year	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
1971	55.62	55.79	56.14	56.47	54.84	36.69
1972	55.42	55.72	56.06	56.37	55.26	37.75
1973	55.54	55.81	56.18	56.50	55.97	39.76
1974	55.42	55.71	56.03	56.37	55.50	40.31
1975	53.97	54.31	54.60	54.89	53.33	30.90
1976	54.94	55.26	55.56	55.87	53.69	30.73
1977	53.93	54.26	54.54	54.85	52.94	31.94
1978	54.89	55.17	55.53	55.84	54.78	34.63
1979	55.68	55.98	56.30	56.64	56.15	43.37
1980	54.24	54.56	54.89	55.27	51.84	33.22
1981	55.12	55.41	55.76	56.07	53.89	36.20
1982	55.28	55.59	55.93	56.23	53.58	40.14
1983	54.86	55.13	55.50	55.82	54.50	33.70
1984	54.81	55.12	55.41	55.78	54.44	37.41
1985	53.42	53.77	54.01	54.29	52.16	28.37
1986	52.63	52.91	53.21	53.51	50.81	25.93
1987	53.90	54.19	54.45	54.87	53.03	31.97
1988	52.00	52.30	52.64	52.97	50.14	26.94
1989	54.49	54.76	55.13	55.44	53.36	35.84
1990	53.29	53.69	54.12	54.16	52.52	32.53
1991	54.27	54.65	55.17	55.19	53.19	34.99
1992	54.07	54.32	54.68	55.01	52.53	32.26
1993	53.16	53.46	53.80	54.18	51.61	30.49
1994	54.59	54.85	55.23	55.50	54.30	37.37
1995	53.59	53.88	54.21	54.62	52.41	28.90
1996	53.83	54.13	54.45	54.76	53.58	34.14
1997	54.86	55.18	55.50	55.79	54.51	36.63
1998	54.59	54.90	55.24	55.63	54.09	36.13
1999	54.41	54.69	55.01	55.33	53.26	34.93
2000	54.88	55.18	55.53	55.83	55.50	36.69
2001	53.99	54.26	54.63	54.92	53.64	30.52

Statistics	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
Average	54.38	54.68	55.01	55.32	53.59	34.24
STDEV	0.89	0.88	0.88	0.89	1.44	4.09
Max	55.68	55.98	56.30	56.64	56.15	43.37
Min	52.00	52.30	52.64	52.97	50.14	25.93
Total	1685.68	1694.94	1705.45	1714.96	1661.36	1061.36

Table D.10. Expected net return for the field for the various irrigation management units over the 31 years of analysis (thousands of dollars) considering a maximum tomato price of $47.04/cwt.

Year	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
1971	548.03	548.14	548.55	548.88	543.23	481.13
1972	547.83	548.11	548.47	548.77	544.84	485.83
1973	547.95	548.14	548.59	548.90	546.11	491.60
1974	547.82	548.08	548.43	548.77	544.69	494.07
1975	546.37	546.67	547.01	547.26	540.74	464.84
1976	547.35	547.67	547.96	548.22	540.51	463.98
1977	546.33	546.61	546.95	547.21	540.13	469.03
1978	547.29	547.53	547.93	548.24	543.40	475.81
1979	548.09	548.38	548.68	549.05	546.42	503.06
1980	546.65	546.94	547.29	547.63	535.95	472.63
1981	547.53	547.77	548.17	548.45	541.10	480.42
1982	547.69	547.97	548.34	548.59	540.23	493.50
1983	547.27	547.48	547.91	548.23	542.47	473.55
1984	547.22	547.52	547.81	548.18	543.54	485.60
1985	545.83	546.13	546.42	546.65	538.51	458.84
1986	545.04	545.27	545.62	545.83	536.12	453.04
1987	546.31	546.59	546.83	547.28	540.83	469.25
1988	544.41	544.69	545.05	545.36	535.60	457.14
1989	546.90	547.12	547.54	547.85	539.54	480.19
1990	545.69	546.05	546.53	546.45	539.69	471.47
1991	546.68	547.03	547.58	547.55	539.58	477.53
1992	546.48	546.66	547.09	547.41	538.86	469.98
1993	545.57	545.84	546.21	546.52	537.63	466.45
1994	547.00	547.17	547.64	547.83	543.21	485.28
1995	546.00	546.27	546.62	546.99	538.91	460.25
1996	546.24	546.51	546.86	547.11	542.00	476.86
1997	547.27	547.59	547.91	548.15	542.79	482.26
1998	546.99	547.30	547.65	548.00	542.26	482.90
1999	546.82	547.05	547.37	547.69	540.42	478.31
2000	547.29	547.55	547.93	548.20	545.85	482.01
2001	546.40	546.57	547.04	547.27	541.62	464.65

Statistics	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
Average	546.79	547.05	547.42	547.70	541.19	475.85
STDEV	0.89	0.88	0.88	0.91	2.88	11.78
Max	548.09	548.38	548.68	549.05	546.42	503.06
Min	544.41	544.69	545.05	545.36	535.60	453.04
Total	16950.36	16958.42	16969.99	16978.55	16776.77	14751.45

Table D.11. Expected net return for the field for the various irrigation management units over the 31 years of analysis (thousands of dollars) considering an average tomato price of $34.47/cwt.

Year	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
1971	282.60	282.74	283.12	283.44	279.96	241.55
1972	282.40	282.69	283.04	283.34	280.93	244.29
1973	282.52	282.75	283.15	283.47	281.90	248.03
1974	282.39	282.67	283.00	283.34	280.99	249.47
1975	280.94	281.27	281.57	281.84	278.00	230.93
1976	281.91	282.24	282.53	282.82	278.09	230.44
1977	280.90	281.21	281.52	281.80	277.51	233.41
1978	281.86	282.12	282.50	282.81	280.01	237.99
1979	282.66	282.95	283.26	283.62	282.14	255.26
1980	281.22	281.52	281.86	282.22	274.99	235.77
1981	282.10	282.36	282.74	283.03	278.47	240.96
1982	282.25	282.55	282.91	283.18	277.90	249.11
1983	281.84	282.08	282.48	282.79	279.43	236.45
1984	281.79	282.09	282.38	282.75	279.89	244.00
1985	280.40	280.72	280.99	281.24	276.34	226.79
1986	279.61	279.86	280.19	280.44	274.51	222.80
1987	280.87	281.17	281.41	281.85	277.88	233.53
1988	278.98	279.27	279.62	279.94	273.91	225.24
1989	281.47	281.72	282.10	282.42	277.47	240.66
1990	280.26	280.64	281.09	281.08	277.08	234.86
1991	281.24	281.61	282.15	282.14	277.39	238.98
1992	281.04	281.26	281.66	281.98	276.71	234.03
1993	280.13	280.42	280.78	281.12	275.64	231.45
1994	281.57	281.79	282.21	282.44	279.66	243.83
1995	280.57	280.85	281.19	281.58	276.66	227.73
1996	280.80	281.09	281.43	281.71	278.71	238.21
1997	281.84	282.16	282.48	282.74	279.58	242.04
1998	281.56	281.87	282.22	282.59	279.11	242.07
1999	281.38	281.64	281.96	282.29	277.81	239.31
2000	281.86	282.13	282.50	282.79	281.53	241.96
2001	280.97	281.19	281.60	281.87	278.57	230.63

Statistics	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
Average	281.35	281.63	281.99	282.28	278.35	237.80
STDEV	0.89	0.88	0.88	0.90	2.09	7.63
Max	282.66	282.95	283.26	283.62	282.14	255.26
Min	278.98	279.27	279.62	279.94	273.91	222.80
Total	8721.92	8730.62	8741.62	8750.69	8628.79	7371.79

Table D.12. Expected net return for the field for the various irrigation management units over the 31 years of analysis (thousands of dollars) considering the 50% percentile tomato price ($30.82/cwt).

Year	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
1971	252.71	252.85	253.23	253.55	250.32	214.57
1972	252.51	252.80	253.15	253.45	251.22	217.09
1973	252.63	252.86	253.26	253.58	252.14	220.61
1974	252.50	252.78	253.11	253.45	251.29	221.93
1975	251.05	251.38	251.68	251.96	248.42	204.58
1976	252.02	252.35	252.64	252.93	248.54	204.14
1977	251.01	251.32	251.63	251.92	247.94	206.88
1978	251.97	252.24	252.61	252.92	250.35	211.21
1979	252.77	253.06	253.37	253.73	252.38	227.36
1980	251.33	251.63	251.97	252.33	245.60	209.09
1981	252.21	252.47	252.85	253.14	248.89	214.00
1982	252.36	252.66	253.02	253.29	248.36	221.59
1983	251.95	252.19	252.59	252.90	249.81	209.75
1984	251.90	252.20	252.49	252.86	250.21	216.79
1985	250.51	250.84	251.10	251.36	246.82	200.66
1986	249.72	249.97	250.30	250.56	245.05	196.88
1987	250.98	251.28	251.52	251.96	248.27	206.99
1988	249.09	249.38	249.73	250.05	244.44	199.13
1989	251.58	251.83	252.21	252.53	247.95	213.69
1990	250.37	250.76	251.20	251.20	247.51	208.22
1991	251.35	251.72	252.26	252.26	247.86	212.11
1992	251.15	251.38	251.77	252.09	247.19	207.46
1993	250.24	250.53	250.89	251.24	246.14	204.98
1994	251.68	251.90	252.32	252.55	249.98	216.64
1995	250.68	250.96	251.30	251.69	247.13	201.55
1996	250.91	251.20	251.54	251.83	249.06	211.34
1997	251.95	252.27	252.59	252.86	249.94	214.99
1998	251.67	251.98	252.33	252.70	249.48	214.95
1999	251.49	251.76	252.07	252.40	248.24	212.39
2000	251.97	252.25	252.61	252.90	251.76	214.93
2001	251.08	251.31	251.71	251.98	248.95	204.28

Statistics	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
Average	251.46	251.75	252.10	252.39	248.75	210.99
STDEV	0.89	0.88	0.88	0.90	2.00	7.16
Max	252.77	253.06	253.37	253.73	252.38	227.36
Min	249.09	249.38	249.73	250.05	244.44	196.88
Total	7795.33	7804.11	7815.04	7824.17	7711.26	6540.78

Table D.13. Expected net return for the field for the various irrigation management units over the 31 years of analysis (thousands of dollars) considering the 25% percentile tomato price ($28.40/cwt).

Year	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
1971	208.60	208.75	209.12	209.45	206.57	174.76
1972	208.40	208.70	209.04	209.35	207.36	176.96
1973	208.52	208.76	209.16	209.47	208.24	180.13
1974	208.39	208.68	209.01	209.35	207.47	181.28
1975	206.94	207.28	207.58	207.85	204.76	165.72
1976	207.92	208.24	208.54	208.83	204.94	165.33
1977	206.90	207.22	207.52	207.81	204.30	167.73
1978	207.86	208.13	208.50	208.81	206.58	171.69
1979	208.66	208.95	209.27	209.62	208.47	186.19
1980	207.22	207.53	207.86	208.23	202.24	169.73
1981	208.10	208.37	208.74	209.04	205.25	174.21
1982	208.26	208.56	208.91	209.19	204.77	180.98
1983	207.84	208.09	208.48	208.80	206.10	170.35
1984	207.79	208.09	208.38	208.75	206.40	176.65
1985	206.40	206.73	206.99	207.25	203.26	162.10
1986	205.61	205.87	206.19	206.46	201.58	158.62
1987	206.88	207.17	207.42	207.85	204.58	167.82
1988	204.98	205.27	205.62	205.95	200.96	160.59
1989	207.47	207.73	208.11	208.42	204.40	173.89
1990	206.26	206.65	207.10	207.10	203.87	168.90
1991	207.25	207.62	208.15	208.16	204.30	172.47
1992	207.05	207.28	207.66	207.98	203.62	168.25
1993	206.14	206.43	206.78	207.14	202.60	165.93
1994	207.57	207.80	208.21	208.45	206.19	176.52
1995	206.57	206.86	207.19	207.59	203.55	162.91
1996	206.81	207.10	207.43	207.72	205.32	171.68
1997	207.84	208.16	208.48	208.76	206.21	175.08
1998	207.56	207.88	208.22	208.59	205.75	174.93
1999	207.39	207.65	207.97	208.30	204.61	172.68
2000	207.86	208.14	208.50	208.80	207.84	175.04
2001	206.97	207.21	207.61	207.88	205.24	165.39

Statistics	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
Average	207.36	207.64	207.99	208.29	205.08	171.44
STDEV	0.89	0.88	0.88	0.90	1.87	6.47
Max	208.66	208.95	209.27	209.62	208.47	186.19
Min	204.98	205.27	205.62	205.95	200.96	158.62
Total	6428.03	6436.92	6447.75	6456.97	6357.33	5314.52

Table D.14. Expected net return for the field for the various irrigation management units over the 31 years of analysis (thousands of dollars) considering the 75% percentile tomato price ($34.90/cwt).

Year	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
1971	326.99	327.12	327.51	327.83	323.99	281.62
1972	326.79	327.08	327.43	327.73	325.07	284.69
1973	326.91	327.13	327.54	327.86	326.08	288.76
1974	326.78	327.05	327.39	327.73	325.09	290.38
1975	325.33	325.65	325.96	326.23	321.94	270.04
1976	326.30	326.63	326.92	327.20	321.98	269.49
1977	325.29	325.59	325.91	326.19	321.43	272.82
1978	326.25	326.51	326.89	327.20	324.06	277.76
1979	327.05	327.34	327.65	328.01	326.34	296.70
1980	325.60	325.91	326.25	326.60	318.63	275.38
1981	326.49	326.75	327.13	327.42	322.39	281.01
1982	326.64	326.94	327.29	327.57	321.77	289.98
1983	326.23	326.46	326.87	327.18	323.42	276.10
1984	326.18	326.48	326.77	327.14	323.99	284.40
1985	324.79	325.11	325.38	325.63	320.19	265.60
1986	324.00	324.24	324.58	324.83	318.26	261.31
1987	325.26	325.55	325.80	326.24	321.86	272.95
1988	323.37	323.65	324.01	324.33	317.68	264.02
1989	325.86	326.10	326.49	326.81	321.29	280.72
1990	324.65	325.03	325.48	325.46	321.00	274.43
1991	325.63	326.00	326.54	326.53	321.23	278.87
1992	325.43	325.64	326.05	326.37	320.55	273.49
1993	324.52	324.81	325.16	325.51	319.45	270.75
1994	325.96	326.17	326.60	326.82	323.74	284.21
1995	324.96	325.24	325.58	325.96	320.52	266.61
1996	325.19	325.48	325.82	326.10	322.74	278.12
1997	326.23	326.54	326.87	327.13	323.60	282.22
1998	325.95	326.26	326.60	326.97	323.12	282.34
1999	325.77	326.03	326.34	326.67	321.73	279.28
2000	326.25	326.52	326.89	327.17	325.73	282.10
2001	325.36	325.57	325.99	326.25	322.56	269.76

Statistics	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
Average	325.74	326.02	326.38	326.67	322.30	277.61
STDEV	0.89	0.88	0.88	0.90	2.22	8.32
Max	327.05	327.34	327.65	328.01	326.34	296.70
Min	323.37	323.65	324.01	324.33	317.68	261.31
Total	10097.99	10106.58	10117.68	10126.66	9991.40	8605.91

Table D.15. Required tomato price ($/cwt) to break even with the annual costs for considering the different irrigation management layouts over 31 years of analysis.

Year	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
1971	16.95	16.94	16.92	16.90	16.96	17.77
1972	16.96	16.94	16.92	16.90	16.95	17.72
1973	16.95	16.93	16.91	16.90	16.91	17.62
1974	16.96	16.94	16.92	16.90	16.93	17.60
1975	17.04	17.02	17.00	16.99	17.04	18.07
1976	16.98	16.97	16.95	16.93	17.02	18.08
1977	17.04	17.02	17.00	16.99	17.06	18.02
1978	16.99	16.97	16.95	16.93	16.97	17.88
1979	16.94	16.93	16.91	16.89	16.90	17.45
1980	17.02	17.00	16.99	16.96	17.10	17.96
1981	16.97	16.96	16.94	16.92	17.01	17.80
1982	16.96	16.95	16.93	16.91	17.02	17.61
1983	16.99	16.97	16.95	16.93	16.98	17.93
1984	16.99	16.97	16.96	16.94	16.99	17.74
1985	17.07	17.05	17.03	17.02	17.10	18.22
1986	17.11	17.09	17.08	17.06	17.17	18.36
1987	17.04	17.02	17.01	16.99	17.06	18.02
1988	17.14	17.13	17.11	17.09	17.21	18.31
1989	17.01	16.99	16.97	16.96	17.03	17.82
1990	17.07	17.05	17.03	17.02	17.08	18.00
1991	17.02	17.00	16.97	16.97	17.04	17.86
1992	17.03	17.02	17.00	16.98	17.08	18.01
1993	17.08	17.06	17.05	17.02	17.13	18.11
1994	17.00	16.99	16.97	16.95	17.00	17.74
1995	17.06	17.04	17.02	17.00	17.09	18.19
1996	17.04	17.03	17.01	16.99	17.03	17.91
1997	16.99	16.97	16.95	16.94	16.98	17.78
1998	17.00	16.98	16.97	16.94	17.00	17.81
1999	17.01	17.00	16.98	16.96	17.04	17.87
2000	16.99	16.97	16.95	16.93	16.94	17.77
2001	17.03	17.02	17.00	16.98	17.03	18.10

Statistics	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
Average	17.01	17.00	16.98	16.96	17.03	17.91
STDEV	0.049	0.048	0.049	0.049	0.072	0.214
Max	17.14	17.13	17.11	17.09	17.21	18.36
Min	16.94	16.93	16.91	16.89	16.90	17.45

Table D.16. Required tomato price ($/cwt) to break even with the annual costs in MMU_4, considering the different irrigation management layouts over 31 years of analysis.

Year	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
1971	16.96	16.96	16.94	16.93	16.92	21.97
1972	16.99	16.97	16.96	16.95	16.93	21.43
1973	16.98	16.96	16.95	16.94	16.92	20.80
1974	16.98	16.97	16.96	16.94	16.93	20.58
1975	17.05	17.03	17.02	17.00	16.99	24.18
1976	17.02	17.01	16.99	16.98	16.96	24.32
1977	17.05	17.03	17.02	17.00	16.99	23.53
1978	17.01	16.99	16.98	16.96	16.95	22.67
1979	16.97	16.96	16.94	16.93	16.92	19.80
1980	17.04	17.03	17.01	17.00	16.98	23.04
1981	16.98	16.97	16.95	16.94	16.93	22.08
1982	17.00	16.98	16.97	16.96	16.94	20.65
1983	17.00	16.98	16.97	16.96	16.94	22.92
1984	17.04	17.02	17.01	17.00	16.98	21.49
1985	17.08	17.07	17.06	17.04	17.03	25.16
1986	17.13	17.12	17.10	17.09	17.08	26.10
1987	17.07	17.06	17.04	17.03	17.01	23.53
1988	17.16	17.14	17.13	17.11	17.10	25.34
1989	17.03	17.01	17.00	16.98	16.97	22.07
1990	17.07	17.05	17.04	17.03	17.01	23.21
1991	17.04	17.03	17.01	17.00	16.98	22.40
1992	17.04	17.03	17.02	17.00	16.99	23.41
1993	17.10	17.08	17.07	17.06	17.04	23.91
1994	17.00	16.99	16.97	16.96	16.95	21.50
1995	17.08	17.06	17.05	17.04	17.02	24.86
1996	17.07	17.05	17.04	17.03	17.01	22.47
1997	17.03	17.02	17.00	16.99	16.98	21.80
1998	17.02	17.01	17.00	16.98	16.97	21.71
1999	17.05	17.04	17.02	17.01	16.99	22.32
2000	17.03	17.01	17.00	16.98	16.97	21.92
2001	17.06	17.04	17.03	17.02	17.00	24.14

Statistics	Lay_1	Lay_2	Lay_3	Lay_4	Lay_5	Lay_6
Average	17.04	17.02	17.01	16.99	16.98	22.75
STDEV	0.045	0.045	0.045	0.045	0.045	1.517
Max	17.16	17.14	17.13	17.11	17.10	26.10
Min	16.96	16.96	16.94	16.93	16.92	19.80

APPENDIX E

STATISTICAL COMPARISONS

E.1 Statistic test of water applied

Layout

NOTE: 80 obs hidden.

Evaluation of irrigation management layouts
Check equality of stddev for WaterApplied
21:32 Thursday, June 14, 2001

Obs	Layout	nobs	rawmean	stddev	stderr	Levene LeveneF_df	P
1	Lay_1	31	52477.24	17759.47	3189.69	0.011(5,180)	1
2	Lay_2	31	52549.12	17646.55	3169.41	.	
3	Lay_3	31	52520.93	17765.33	3190.75	.	
4	Lay_4	31	52584.10	17770.34	3191.65	.	
5	Lay_5	31	52615.65	18027.99	3237.92	.	
6	Lay_6	31	51713.12	18339.35	3293.84	.	

The Mixed Procedure

Model Information

Data Set	WORK.ONE
Dependent Variable	WaterApplied
Covariance Structure	Variance Components
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Containment

Class Level Information

Class	Levels	Values
Layout	6	Lay_1 Lay_2 Lay_3 Lay_4 Lay_5 Lay_6
Year	31	1971 1972 1973 1974 1975 1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001

E.1 (continued)

Dimensions

Covariance Parameters	2
Columns in X	7
Columns in Z	31
Subjects	1
Max Obs Per Subject	186
Observations Used	186
Observations Not Used	0
Total Observations	186

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	4056.46753260	
1	1	3528.08868759	0.00000000

Evaluation of irrigation management layouts 15
Mixed ANOVA for WaterApplied 21:32 Thursday, June 14, 2001

The Mixed Procedure

Convergence criteria met.

Covariance Parameter Estimates

Cov Parm	Estimate
Year	3.133E8
Residual	6623873

Fit Statistics

-2 Res Log Likelihood	3528.1
AIC (smaller is better)	3532.1
AICC (smaller is better)	3532.2
BIC (smaller is better)	3535.0

E.1 (continued)

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Layout	5	150	0.56	0.7333

Estimates

Label	Estimate	Standard Error	DF	t Value	Pr > |t|
High WHC vs Low WHC	-331.20	2067.24	150	-0.16	0.8729
SS vs Uniform	-4181.44	2531.84	150	-1.65	0.1007

Contrasts

Label	Num DF	Den DF	F Value	Pr > F
High WHC vs Low WHC	1	150	0.03	0.8729
SS vs Uniform	1	150	2.73	0.1007

---------- ADJUSTMENT=Tukey-Kramer(.05) BYGROUP=1 Effect=Layout ----------

Obs	Layout	Estimate	Standard Error	DF	t Value	Pr > |t|	Let Grp
1	Lay_1	52477	3212.49	150	16.34	<.0001	A
2	Lay_2	52549	3212.49	150	16.36	<.0001	A
3	Lay_3	52521	3212.49	150	16.35	<.0001	A
4	Lay_4	52584	3212.49	150	16.37	<.0001	A
5	Lay_5	52616	3212.49	150	16.38	<.0001	A
6	Lay_6	51713	3212.49	150	16.10	<.0001	A

E.1 (continued)

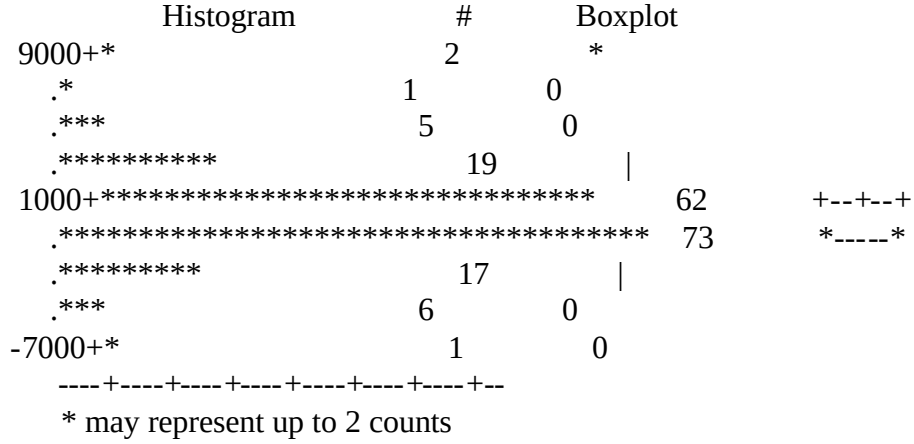
The UNIVARIATE Procedure
Variable: Resid

Tests for Normality

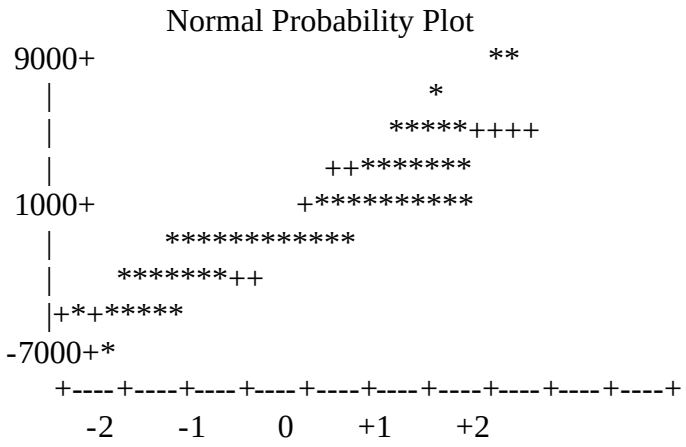
Test		--Statistic---	-----p Value------
Shapiro-Wilk	W	0.957006	Pr < W <0.0001
Kolmogorov-Smirnov	D	0.104204	Pr > D <0.0100
Cramer-von Mises	W-Sq	0.348718	Pr > W-Sq <0.0050
Anderson-Darling	A-Sq	2.060724	Pr > A-Sq <0.0050

Extreme Observations

------Lowest-----		-----Highest-----	
Value	Obs	Value	Obs
-7251.26	175	5180.44	168
-5812.06	176	5333.17	171
-5431.86	137	7540.54	161
-5321.01	160	8310.50	136
-5201.43	185	9382.56	183



The UNIVARIATE Procedure
Variable: Resid



E.2 Statistic test of cost of fuel

Layout

NOTE: 77 obs hidden.

Evaluation of irrigation management layouts 21
Check equality of stddev for Fuel 21:32 Thursday, June 14, 2001

Obs	Layout	nobs	rawmean	stddev	stderr	Levene F_df	Levene P
1	Lay_1	31	2610.15	890.525	159.943	0.01(5,180)	1
2	Lay_2	31	2617.93	879.128	157.896	.	
3	Lay_3	31	2616.52	885.046	158.959	.	
4	Lay_4	31	2619.67	885.295	159.004	.	
5	Lay_5	31	2621.24	898.131	161.309	.	
6	Lay_6	31	2576.28	913.643	164.095	.	

Evaluation of irrigation management layouts 22
Mixed ANOVA for Fuel 21:32 Thursday, June 14, 2001

The Mixed Procedure

Model Information

Data Set	WORK.ONE
Dependent Variable	Fuel
Covariance Structure	Variance Components
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Containment

Class Level Information

Class	Levels	Values
Layout	6	Lay_1 Lay_2 Lay_3 Lay_4 Lay_5 Lay_6
Year	31	1971 1972 1973 1974 1975 1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001

E.2 (continued)

Dimensions

Covariance Parameters	2
Columns in X	7
Columns in Z	31
Subjects	1
Max Obs Per Subject	186
Observations Used	186
Observations Not Used	0
Total Observations	186

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	2977.08291540	
1	1	2449.40009125	0.00000000

Evaluation of irrigation management layouts 23
Mixed ANOVA for Fuel 21:32 Thursday, June 14, 2001

The Mixed Procedure

Convergence criteria met.

Covariance Parameter Estimates

Cov Parm	Estimate
Year	779171
Residual	16552

Fit Statistics

-2 Res Log Likelihood	2449.4
AIC (smaller is better)	2453.4
AICC (smaller is better)	2453.5
BIC (smaller is better)	2456.3

E.2 (continued)

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Layout	5	150	0.55	0.7400

Estimates

Label	Estimate	Standard Error	DF	t Value	Pr > |t|
High WHC vs Low WHC	-20.6947	103.34	150	-0.20	0.8415
SS vs Uniform	-204.12	126.56	150	-1.61	0.1089

Contrasts

Label	Num DF	Den DF	F Value	Pr > F
High WHC vs Low WHC	1	150	0.04	0.8415
SS vs Uniform	1	150	2.60	0.1089

---------- ADJUSTMENT=Tukey-Kramer(.05) BYGROUP=1 Effect=Layout ----------

Obs	Layout	Estimate	Standard Error	DF	t Value	Pr > |t|	Let Grp
1	Lay_1	2610.15	160.21	150	16.29	<.0001	A
2	Lay_2	2617.93	160.21	150	16.34	<.0001	A
3	Lay_3	2616.52	160.21	150	16.33	<.0001	A
4	Lay_4	2619.67	160.21	150	16.35	<.0001	A
5	Lay_5	2621.24	160.21	150	16.36	<.0001	A
6	Lay_6	2576.28	160.21	150	16.08	<.0001	A

E.2 (continued)

The UNIVARIATE Procedure
Variable: Resid

Tests for Normality

Test	--Statistic---	-----p Value------
Shapiro-Wilk	W 0.958037	Pr < W <0.0001
Kolmogorov-Smirnov	D 0.106194	Pr > D <0.0100
Cramer-von Mises	W-Sq 0.339448	Pr > W-Sq <0.0050
Anderson-Darling	A-Sq 2.016949	Pr > A-Sq <0.0050

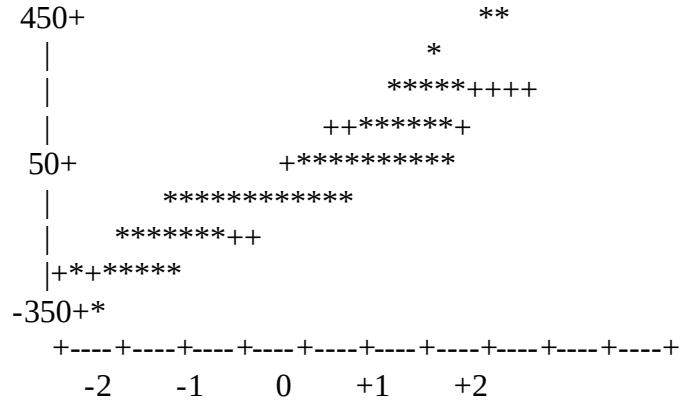
Extreme Observations

------Lowest-----		-----Highest-----	
Value	Obs	Value	Obs
-361.930	175	257.378	168
-290.247	176	265.026	171
-271.313	137	374.956	161
-265.777	160	413.308	136
-259.835	185	466.728	183

```
          Histogram                #          Boxplot
 450+*                             2            *
   .*                              1            0
   .***                            6            0
   .*********                     18           |
  50+*********************************         62          +--+--+
   .************************************       72          *-----*
   .*********                     18           |
   .***                           6            0
-350+*                            1            0
    ----+----+----+----+----+----+----+-
    * may represent up to 2 counts
```

The UNIVARIATE Procedure
Variable: Resid

Normal Probability Plot



E.3 Statistic test of tomato production

Layout

NOTE: 163 obs hidden.

Check equality of stddev for Tomato_Prod

21:32 Thursday, June 14, 2001

Obs	Layout	nobs	rawmean	stddev	stderr	Levene	F_df	P
1	Lay_1	31	18208.97	0.000	0.0000	18.478	(5,180)	0
2	Lay_2	31	18207.54	0.937	0.1683	.		
3	Lay_3	31	18208.81	0.403	0.0724	.		
4	Lay_4	31	18207.68	1.093	0.1963	.		
5	Lay_5	31	18030.92	56.322	10.1158	.		
6	Lay_6	31	16330.68	284.981	51.1841	.		

Mixed ANOVA for Tomato_Prod 21:32 Thursday, June 14, 2001

The Mixed Procedure

Model Information

Data Set	WORK.ONE
Dependent Variable	Tomato_Prod
Covariance Structure	Variance Components
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Containment

Class Level Information

Class	Levels	Values
Layout	6	Lay_1 Lay_2 Lay_3 Lay_4 Lay_5 Lay_6
Year	31	1971 1972 1973 1974 1975 1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001

E.3 (continued)

Dimensions

Covariance Parameters	2
Columns in X	7
Columns in Z	31
Subjects	1
Max Obs Per Subject	186
Observations Used	186
Observations Not Used	0
Total Observations	186

Iteration History

Iteration	Evaluations	-2 Res Log Like	Criterion
0	1	2250.67871372	
1	1	2249.61364520	0.00000000

Evaluation of irrigation management layouts 31
Mixed ANOVA for Tomato_Prod 21:32 Thursday, June 14, 2001

The Mixed Procedure

Convergence criteria met.

Covariance Parameter Estimates

Cov Parm	Estimate
Year	727.16
Residual	13338

Fit Statistics

-2 Res Log Likelihood	2249.6
AIC (smaller is better)	2253.6
AICC (smaller is better)	2253.7
BIC (smaller is better)	2256.5

E.3 (continued)

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Layout	5	150	1326.20	<.0001

Estimates

Label	Estimate	Standard Error	DF	t Value	Pr > |t|
High WHC vs Low WHC	709.33	92.7626	150	7.65	<.0001
SS vs Uniform	-9210.53	113.61	150	-81.07	<.0001

Contrasts

Label	Num DF	Den DF	F Value	Pr > F
High WHC vs Low WHC	1	150	58.47	<.0001
SS vs Uniform	1	150	6572.53	<.0001

---------- ADJUSTMENT=Tukey-Kramer(.05) BYGROUP=1 Effect=Layout ----------

Obs	Layout	Estimate	Standard Error	DF	t Value	Pr > |t|	Let Grp
1	Lay_1	18209	21.3003	150	854.87	<.0001	A
2	Lay_2	18208	21.3003	150	854.80	<.0001	A
3	Lay_3	18209	21.3003	150	854.86	<.0001	A
4	Lay_4	18208	21.3003	150	854.81	<.0001	A
5	Lay_5	18031	21.3003	150	846.51	<.0001	B
6	Lay_6	16331	21.3003	150	766.69	<.0001	C

E.3 (continued)

The UNIVARIATE Procedure
Variable: Resid

Tests for Normality

Test	--Statistic---	-----p Value------
Shapiro-Wilk	W 0.652614	Pr < W <0.0001
Kolmogorov-Smirnov	D 0.274455	Pr > D <0.0100
Cramer-von Mises	W-Sq 5.071613	Pr > W-Sq <0.0050
Anderson-Darling	A-Sq 24.79816	Pr > A-Sq <0.0050

Extreme Observations

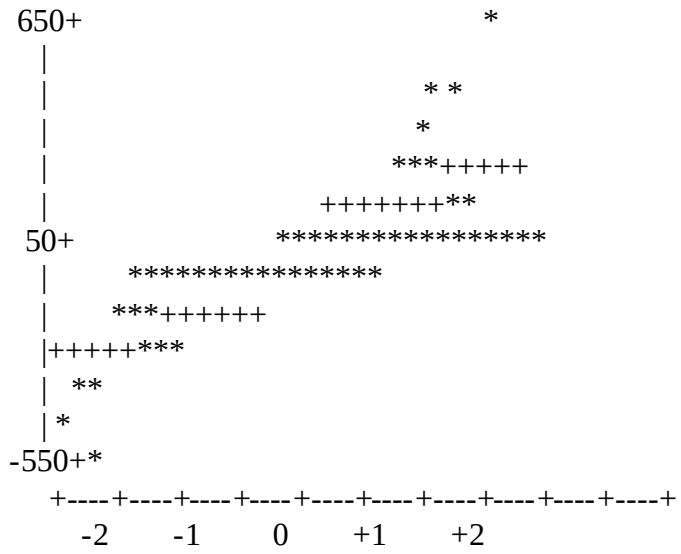
------Lowest-----		-----Highest-----	
Value	Obs	Value	Obs
-510.633	171	230.577	169
-401.520	173	358.683	158
-393.276	170	417.916	167
-362.275	180	428.107	159
-295.475	161	636.497	164

```
          Histogram                #          Boxplot
650+*                              1            *
   .
   .*                              2            *
   .*                              1            *
   .**                             3            *
   .**                             3            *
 50+****************************************    81          +--0--+
   .****************************************   83          *--0--*
   .***                            5            *
   .**                             3            *
   .*                              2            *
   .*                              1            *
-550+*                             1            *
    ----+----+----+----+----+----+----+----+--
    * may represent up to 2 counts
```

E.3 (continued)

The UNIVARIATE Procedure
Variable: Resid

Normal Probability Plot



Vita

Carlos Wagner Oliveira was born in Bela Cruz, Ceará, Brazil on May 9, 1970. He entered the Federal University of Ceará in February, 1989, and received a degree of Bachelor of Science in Agronomic Engineering in June, 1994. After graduation, he provided consulting assistance to the city of Barreira, Ceará.. He then reenters the Federal University of Ceará in February 1995, and received a Master of Science degree in Irrigation and Drainage. During his master's studies he spent two months in The University of Tennessee, Knoxville as a visitor scholar in 1997. After completion of his master's he worked part time in a consulting firm PIVOT and as a research scholar for Cearence Research Foundation – FUNCAP. In 1999, he decided to pursue his doctoral degree at The University of Tennessee, Knoxville. He was first enrolled in The Department of Biossytems Systems and Environmental Science, as a Graduate Research Assistant. Currently, he is sponsored by a grant scholarship from the Brazilian National Council for Scientific and Technological Development – CNPq.