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RISK ANALYSIS OF SUBIRRIGATION INVESTMENT DECISIONS IN THE SAGINAW BAY AREA OF MICHIGAN

BY

KATHERINE KAMPMANN

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ABSTRACT

RISK ANALYSIS OF SUBIRRIGATION INVESTMENT DECISIONS FOR CORN PRODUCTION IN THE SAGINAW BAY AREA OF MICHIGAN

By

Katherine Kampmann

This thesis examines on-farm investment and operating costs and financial benefits of two improved drainage and six subirrigation investments on a representative field in the Saginaw Bay Area of Michigan. Net present values (NPVs) are generated from a base sequence and from random sequences of corn yields simulated from historical weather data in Michigan. Under both certainty and risk, the surface water subirrigation system at 60-ft tile spacing is the most profitable investment. For the 1958-87 actual weather sequence, the existing drainage-only system is dominated by two surface and one well water source subirrigation systems and dominates the other subirrigation and narrower-spaced drainage-only systems. Under random weather conditions, subirrigation with surface water at 30- and 60-ft tile spacings dominates the other systems by first or second degree stochastic dominance, so long as the price of corn remains above $2.05/bu (or $3.00/bu for the well water source).

This thesis is dedicated to Jeff, who saw me through the endeavor, and my parents, who have always encouraged me to endeavor.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1. Introduction

Excessive or deficient soil water conditions are potentially the most limiting factors in corn production. For more than a century, farmers in Michigan and other states have used surface and subsurface drainage to manage excessive water. Drainage allows farmers to begin planting operations earlier in the spring and ensures that they can begin harvest in a timely manner in the fall. In addition, it allows them to remove excessive soil water to ensure a suitable environment for crop growth during the growing season.

In the Saginaw Bay Area of Michigan, many farmers are improving their drainage systems by reducing the spacing between tiles to benefit from improved drainage. Some are also adapting their drainage systems to serve a dual role as a subsurface irrigation system, or subirrigation system. A subirrigation system is a drainage system that has been modified by installing control structures and irrigation risers and developing a water supply system to pump water into the drainage tiles during the growing season to supply supplementary water to crops. Retrofitting a subsurface drainage system for subirrigation often also entails reducing the tile spacing in order to ensure that the water table can be maintained at a more uniform level in the field.

Through this new water table management system (WTMS) approach, farmers can not only remove water from fields under excessive water conditions, but can also pump water back into the drainage tiles and maintain adequate soil moisture throughout the growing season. Their ability to manage the water availability conditions in their fields under both excessive and deficient soil water conditions allows them to control much of the yield risk they face.

Investing in an improved WTMS has risks of its own, however. Making any investment decision involves financial risk. The farmer must determine if the increased yield benefit or reduced yield variability from improved drainage or subirrigation provides enough additional revenue or stabilizes revenue sufficiently to justify the investment cost. But in humid climates, these benefits are very dependent on the rainfall pattern in the years following the investment. For a drainage-only system, in most years the tile spacing might be adequate, but in particularly wet years, improved drainage might mean the difference between meeting and not meeting planting time constraints. Similarly, with subirrigation in humid regions, rainfall is adequate in many years to produce acceptable yields of major field crops grown in Michigan: corn, dry beans, sugar beets, and soybeans. Without taking the financial risk of investing in irrigation, farmers can still produce these crops. For a given planning horizon, the profitability of both types of improved WTMS investment over the existing drainage-only[1] system hinges on the particular pattern of rainfall following the investment. For example, with subirrigation if rainfall is adequate in the first few years following the investment, the additional yield benefit of the system is small and the payback period is lengthened, which greatly lowers the net present value (NPV) of the investment. If, on the other

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[1] "Drainage only" refers to conventional subsurface drainage.

hand, rainfall is poor following the investment, the additional yield benefit is large, and the system pays for itself more quickly, resulting in a larger NPV for the entire planning horizon.

The question facing farmers is how to assess these issues and make the right investment choice. Past economic analyses of subirrigation and drainage have provided some measures of the net returns to subirrigation or improved drainage under actual field conditions for a limited number of years' field data and under simulated conditions for more extensive time periods, providing decision makers with an idea of the economic benefit of the WTMS investment for a particular sequence of weather. But they have not provided answers to the larger question of what are the expected returns to an investment in a WTMS given other possible sequences of weather. The present analysis attempts to answer that question.

In addition, past economic studies of WTMS have presented results in terms of mean values but have not adequately assessed whether subirrigation or improved drainage reduces income variability, and if so, how this benefit should be quantified for risk averse farmers. This study looks specifically at the risk implications of investing in a WTMS for farmers with varying risk attitudes.

Huron County, in the Saginaw Bay area of Michigan, is the hypothetical site of this economic analysis. A major impetus for choosing Huron County as the setting for the analysis is that county farmers are currently installing improved drainage and subirrigation systems. In addition, studies of subirrigation potential have identified the five counties of the Saginaw Bay area as having the greatest concentration of acres with high subirrigation potential in Michigan (Belcher, 1990a). Of those five counties, Huron County has the largest number of acres of land suitable for subirrigation. On the other hand, it also has limited ground and surface water available for further expanding subirrigation. Already in some rural townships, ordinances have been passed to limit groundwater pumping for subirrigation.

This limitation has framed the context of the current analysis. If subirrigation is to continue to expand in Huron County, water sources other than groundwater need to be developed. The Saginaw Bay provides a vast supply of potential water for irrigation. If irrigation districts could be established, the large irrigation potential of Huron County could be tapped. But subirrigation would not only have to provide adequate on-farm benefits to offset on-farm costs, it would have to offset irrigation district development, maintenance, and operating costs. A preliminary study of the economic and technical feasibility of establishing an irrigation district to draw water from the Saginaw Bay to bring water to farmers in areas that are particularly suitable for subirrigation has shown that water costs to farmers in such an irrigation district could range between $25 and $35 per acre (Williams et al., 1990). This cost would be additional to on-farm costs of developing a subirrigation system and pumping water from the district irrigation canal to the farmer's fields. The present economic analysis should provide a measure of the on-farm benefit of subirrigation over drainage only that could be used as a benchmark for what farmers might be willing to pay to participate in an irrigation district.

Because some farmers do have access to ground water, the economic analysis is done for both a well water source and a surface water source. The surface water investment and operating costs mimic the on-farm costs that a farmer would experience if pumping from a private surface water source or an irrigation district canal. Operating and investment costs for a well water source are substantially higher than for a surface water source because the well drilling cost has to be considered as part of the subirrigation WTMS investment. The results for the well water source subirrigation investment could provide farmers who are considering developing a private well or participating in an irrigation district with a measure of the return from each option.

The analysis begins with the assumption that continuous corn is being grown on a 40 acre field that has a Kilmanagh soil and an existing drainage system with tiles spaced at 60-ft intervals. The strategies evaluated include modifying the existing drainage-only WTMS by reducing the drain spacing to 20 feet (DR20) or 30 feet (DR30), keeping the existing drainage-only system intact (DR60), converting the existing drainage-only WTMS into a subirrigation system at 20-ft tile spacings for a surface water source (SI20S) or a well water source (SI20W), or into a subirrigation system at 30-ft tile spacings for a surface water source (SI30S) or a well water source (SI30W), or into a subirrigation system at 60-ft tile spacings for a surface water source (SI60S) or a well water source (SI60W).

1.2. Objectives

The objectives of this study are the following:

(1) Determine the economic benefit of converting the existing drainage-only WTMS to a drainage-only system at 20- and 30-ft tile spacings.

(2) Determine the economic benefit of converting the existing drainage-only WTMS to a subirrigation WTMS at 20-, 30-, and 60-ft tile spacings for a surface water source.

(2a) Determine if the benefit of subirrigation with a surface water source is large enough at the farm level to offset the water use fees if an irrigation district were established which could provide water to farmers at a charge of $25-$35/acre.

(3) Determine the economic benefit of converting a drainage-only WTMS to a subirrigation WTMS at 20-, 30-, and 60-ft tile spacings for a well water source.

(3a) Compare the difference in benefit of subirrigation with a well water source and a surface water source with potential irrigation district water use fees to determine if a farmer without access to a private surface water source would be better off drilling a well or participating in the irrigation district.

Two approaches are taken in the analysis. First, the economic analysis is performed using a given series of yields derived from a simulation model run with weather that occurred in Flint, Michigan from 1958 to 1990. This is similar to the approaches taken to date in evaluating subirrigation. Second, random yield sequences are drawn from the simulation yield data. Results from the two approaches are compared. Finally, results from the second approach are analyzed both under certainty and under risk.

1.3. Methods

The analysis proceeds in seven stages.

(1) The production and investment costs associated with growing corn under different WTMSs are determined.

(2) The simulation model DRAINMOD is used to generate corn yields and irrigation application amounts for different WTMSs over a 33-year period of historic weather data.

(3) A net present value (NPV) analysis under the base weather sequence is performed using the cost data and the output of DRAINMOD. The NPVs of the various WTMS options are compared.

(4) Monte Carlo simulation is used to generate probability distributions of NPVs to capture the effect of weather variability on NPV.

(5) Expected net present values (ENPV) of the various WTMS options are calculated and compared across systems. The NPVs from the base weather sequence are compared with the ENPVs.

(6) The probability distributions of NPV generated in the Monte Carlo simulation are compared in three stages:

a) using expected value-variance (EV) efficiency criteria;

b) using first and second degree stochastic dominance (FSD and SSD) criteria;

c) using stochastic dominance with respect to a function efficiency criteria to compare those distributions which are not stochastically dominated by FSD or SSD.

(7) A sensitivity analysis is performed to compare the outcome of the base analysis with outcomes of analyses run with a range of product prices, investment costs, financial parameters, and yield assumptions.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

The focus of this literature review is subirrigation. Drainage is always an integral component of any subirrigation system and is thus encompassed. It also receives some attention individually, but subirrigation is a new technology compared with drainage and hence is highlighted.

Literature on subirrigation can be divided into three main categories: technical aspects, water quality impacts, and economic feasibility. In addition to economic studies that look specifically at subirrigation, there is a large body of literature on economic aspects of irrigation in general. The purpose of this literature review is to summarize the most important conclusions of studies of technical and water quality issues related to subirrigation and to focus on the economic studies of subirrigation and irrigation.

The results of a selection of technical and water quality impact studies are summarized in section 2.2 below. In section 2.3, a selective overview of the findings of economic analyses of irrigation in humid climates is presented. A more extensive presentation of the available economic studies of subirrigation follows in section 2.4, Section 2.5 highlights the strengths of available economic analyses and the gaps that need to be filled. These provide the guidelines of the approach to be taken in the current economic analysis.

2.2. Technical Aspects of Subirrigation

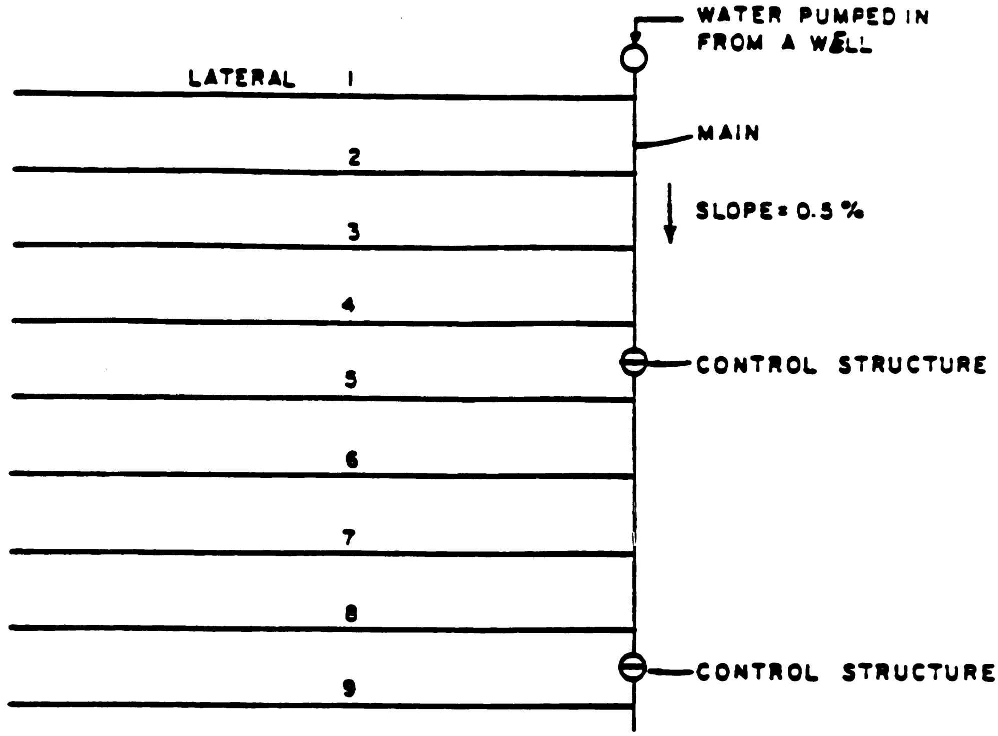
Michigan has 3 million acres of poorly drained agricultural land (USDA, 1982). Subsurface drainage tiles make many of these acres of poorly drained, high water table fields productive for agriculture. The necessity of providing drainage and the frequent use of subsurface drainage tiles as the drainage system of choice make subirrigation through those same drainage tiles technically feasible. Below, the technical aspects of subirrigation are described and the soil and land characteristics that make subirrigation feasible are noted. Based on these characteristics, the areas in Michigan with high potential are identified. Finally, available water resources are assessed in those areas with high subirrigation potential.

2.2.1. Subirrigation Defined and Described

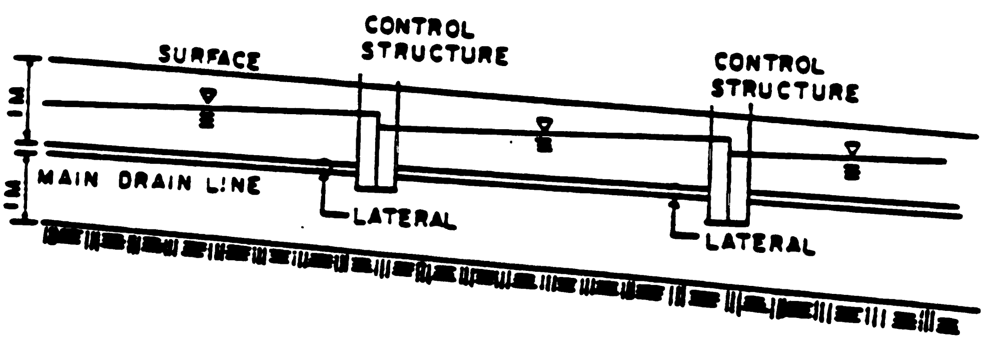
Subirrigation is a method of providing supplementary soil moisture to crops. A subirrigation system is generally a subsurface tile drainage system that has been modified so that the drainage tiles serve a dual role of removing excess water and supplying supplementary water to meet crop needs. Figure 2.1. shows the layout of a subsurface drainage-subirrigation system. The system components include a main water pipe, perforated laterals, water control structures, and an irrigation intake riser. The main water pipe carries water from the water source to the laterals during subirrigation and collects water from the laterals during drainage and carries the water to either a drainage canal or some other receiving system. The laterals are perforated pipes, usually of corrugated plastic. Water seeps into them during drainage and out of them during subirrigation. The control structure houses the weir which when raised or lowered controls the water table level in the field. The irrigation intake riser receives the

Figure 2.1. Profile and Overhead View of a Drainage-Subirrigation System

Overhead View of Drainage/Subirrigation System



Profile View of Drainage/Subirrigation System



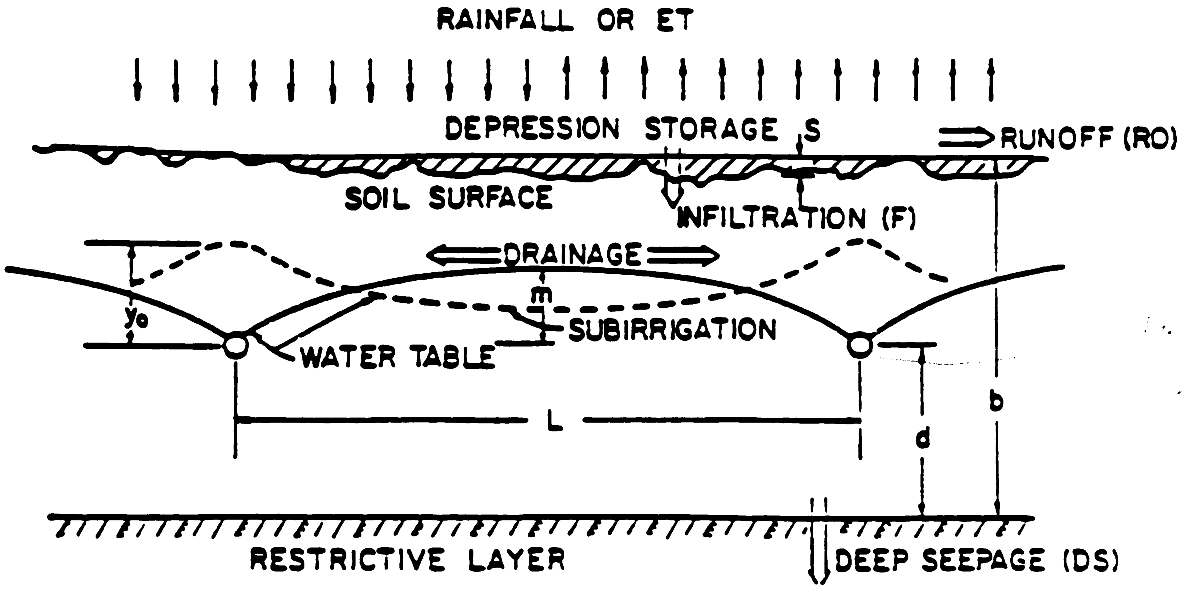
Source: Skaggs, 1981, p. 8-5.

irrigation water from the water source before it is distributed through the main water pipe to the laterals.

The principle behind drainage-subirrigation systems is to manage the water table (Figure 2.2.). The water table is lowered during drainage by allowing water to move freely from the tile laterals into the main and out of the field. This provides trafficable conditions during planting and harvest and removes excess water after a heavy rainfall during the growing season. As can be seen in Figure 2.2., drainage between laterals is slower than directly over the laterals, creating a dome effect on the water table. During subirrigation, water is pumped from the main into the perforated subsurface drainage tiles, raising the water table enough to maintain an adequate water supply just below the root zone of the crop. Soil capillary action and diffusion draw water upward from the water table into the unsaturated root zone, replenishing water which plants remove during evapotranspiration (ET). As in the case of drainage, during subirrigation, water movement into the soil is not always uniform. Over the tiles the water table bulges upward and between the laterals it scoops downward.

A subirrigation system can be operated in either of two ways. The most common procedure is to maintain a constant water level elevation in the tile outlet. Water is periodically pumped into the tiles to replenish water which moves from the drains into the soil to supply ET demands and seepage losses. A second procedure is to pump water into the root zone of the soil profile. After pumping is stopped, the water table level is allowed to fall to some predetermined level before pumping is initiated again (Skaggs, 1981).

Figure 2.2. Schematic of Water Table Management



Source: Skaggs, 1981, p. 2-1.

2.2.2. Soil and Land Characteristics

Soil properties are among the most important considerations when assessing the potential for subirrigation (Kittleson et al., 1990a). The most important soil factor in subirrigation is the presence or absence of a barrier layer within 72 inches of the soil surface. This barrier is a natural feature of poorly drained soils. It slows the downward movement of water into the soil and produces a shallow water table. It is the barrier layer and the shallow water table that make water table management both necessary and feasible. Necessary, because drainage tiles must be used to remove excess water from fields for planting and harvest operations when heavy equipment requires trafficable field conditions. Feasible, because with the barrier, water pumped into the tiles through a subirrigation system is prevented from draining immediately through the soil layers and moving beyond reach of the plant roots.

Other soil factors, such as soil texture, permeability in the top 40 inches and in the 40- to 60-inch layer, depth to bedrock, and depth to the barrier layer determine the suitability of soil for subirrigation (Kittleson et al., 1990a).

Field slope also affects the feasibility of subirrigation. Land with a slope greater than 2% should not be considered for subirrigation, while land with a slope of between 0 and 1% has a high potential for subirrigation. Slope is an important determinant because for subirrigation to be practicable, the water table needs to be kept at a relatively uniform level throughout the field. If there is too much slope to a field, several zones need to be established within the field and a control stand installed for each zone (Figures 2.1. and 2.2.). A control stand should be installed in the main subirrigation line for every 0.5% change in slope in the field. If the field slope is greater than 2%, adding the extra control stands necessary to maintain a uniform water table level in the field increases the cost of the subirrigation system.

Based on the above criteria, researchers at Michigan State University's Institute of Water Research and at the Soil Conservation Service estimate that 492,192 acres, or 19.9% of the agricultural land, in the five counties of the Saginaw Bay area have high potential for subirrigation. Huron county has the largest number of acres of highly suitable land, with 353,234 acres. In the five county area, another 1,497,433 acres (59.8%) have medium potential. Thus, 80% of the agricultural land in the study area has either high or medium potential for subirrigation based on soil property criteria alone (Kittleson et al., 1990a).

2.2.3. Water Availability

Irrigation, both sprinkler and subirrigation, has expanded rapidly in Michigan in the last decade. In Huron County, the hypothetical site of the present economic analysis, in the 11-year period between 1978 and 1988 irrigation acreage increased 500% from 438 acres to 2200 acres (Michigan Department of Agriculture, 1990; LeCureux and Booms, 1990a). In 1987, the total irrigated acreage in Michigan was 15,035 acres, up from 8,460 acres in 1978 (U.S. Department of Commerce, 1978 and 1987). While the total irrigated acreage for Michigan is still quite low, there has already been concern about increasing water demand for irrigation in rural townships in the Saginaw Bay Area. Some townships have established water use ordinances to limit the continuous operation of high volume irrigation wells. In Huron County, township administrators are considering ordinances that would require farmers to obtain permits to pump groundwater for agricultural purposes (Kittleson et al., 1990b).

Several studies have been made of water availability for irrigation in the Saginaw Bay area. One study showed that over 83% of the high suitability soils and 55% of the medium suitability soils are located over geologic formations containing no significant aquifer. In Huron County, which has the largest number of acres of highly suitable land for subirrigation, only 19,659 of the 324,000 suitable acres are over an aquifer (Kittleson et al., 1990a). The authors concluded that if major expansion of subirrigation occurs on high suitability soils using groundwater, shortages of groundwater and/or decreases in groundwater quality will develop almost immediately in most areas (Kittleson et al., 1990a).

Considering surface water availability, a recent study by the Department of Resource Development at Michigan State University (He et al., 1991) estimated that although 68.1% of the land in the Saginaw Bay area that is within two kilometers of surface water supplies that have year-round water, a maximum of 44,105 acres (2.2% of the total agricultural land in the Saginaw Bay area) can be irrigated by stream flow in the watersheds in the five Bay counties for which stream flow data are available. This estimate is based on three assumptions. First, it is based on irrigation water demand at the 75% probability level, which means that irrigation demand in a particular year will be smaller than the calculated value 75% of the time (He et al., 1991, p.13). Second, it is based on a 75% exceedence flow, which indicates that stream flow will exceed or equal the specified value 75% of the time. Third, it is also based on the assumption that stream water is drawn down to the 95% exceedence level. This is the flow level set by the National Pollutant Discharge Elimination System (NPDES) for effluent limits. If withdrawals did in fact occur up to the 95% exceedence level on a regular basis, however, they would "seriously degrade the quality of the stream" (He et al., 1991).

The largest source of water in the Saginaw Bay Area is Lake Huron. Agricultural producers bordering the lake at Saginaw Bay can and do use bay water to irrigate their crops. In fact, most growers who have access to lake-level water irrigate their crops (Spicer, 1990). Currently, the legal use of lake water for irrigation is limited to lands that are riparian to Lake Huron or to a tributary stream. Access varies depending on the lake level, which fluctuates as much as 6.59 feet at the extremes (Spicer, 1990). The Kittleson et al. (1990a) study mentioned previously showed that there are 37,561 acres of highly suitable land within 2.5 miles of Lake Huron, with 34,074 of these acres in Huron County. Another 72,816 acres of medium suitability soil fall within this same distance, and 11,861 of these are in Huron County.

The limited availability of suitable stream and ground water and the elevated costs of developing groundwater sources have stimulated interest in exploring the feasibility of establishing irrigation districts to draw water from Saginaw Bay. Several engineering studies of costs of constructing an irrigation district have been commissioned by the Saginaw Bay Subirrigation/Drainage (SBSD) project (Spicer, 1990; Williamson & Associates, 1990; Williams et al., 1990).

One study of a proposed 24,000 acre district in Huron County falling within the Caseville, Lake, McKinley, and Chandler Townships (Williams et al., 1990) estimated that for a system designed at a capacity to deliver 8 inches of water in 40 days to 50% of the area farmland, the total annual cost would be between $25 and $35 per acre. These estimates include amortization of the construction costs and annual operation and maintenance costs, assuming 8% financing over 20 years. These figures are only for delivery of the water to a farmer's field. Once delivered, water must be distributed and the costs of the on-farm distribution system are additional costs.

A second study (Spicer, 1990) reports that a 2,400 acre Mud Creek Irrigation District in Huron County is being established to withdraw water from Saginaw Bay. Their estimates are that the average cost per acre for a district encompassing 5 miles of land from the bay inland would be $841, which translates into an average annual cost of $32.30 per acre, based on a 20 year depreciation period and 8% interest. These costs include construction costs, interest, electricity, and maintenance costs. In this case, farmers would again incur additional costs to bring the water from the irrigation ditch to their fields.

The per-acre cost estimates of establishing the irrigation districts necessary to pump from the bay are relatively high given that farmers must then incur additional costs to bring the water to their fields. Part of the impetus of the current economic analysis of subirrigation and others done in Huron County is to determine if the benefits of subirrigation are large enough at the farm level to cover additional costs of water brought to farmers through an irrigation district at a per-acre cost of as much as $35. The results of on-farm economic studies will establish whether irrigation expansion should be limited to acreage that can be irrigated with surface water (other than lake water) and ground water, or whether it will be economically viable to establish irrigation districts and greatly expand irrigated acreage through the use of lake water.

2.2.4. Water Quality Aspects of Subirrigation

Water quality research has focused on whether subirrigation results in more or less contaminants being discharged into tile effluent, being lost to surface water runoff, or remaining in the field than conventional subsurface drainage or surface-only drainage systems. Results are rather mixed. Two researchers at Michigan State University's Department of Agricultural Engineering summarized the results of 43 research reports published in scientific journals and 18 additional research articles in a literature review of water table management impacts on water quality (Fogiel and Belcher, 1991). They concluded from the studies that the primary impact of water table management is on receiving surface waters (as opposed to groundwater) and that in general, subsurface drainage systems reduce runoff and therefore result in less sediment and fewer pollutants attached to soil particles being delivered to surface waters. However, some studies showed that improper management of subsurface drainage systems can result in increased nitrate nitrogen concentrations and loadings being delivered to receiving waters.

Only two of the studies Fogiel and Belcher reviewed looked specifically at the effects of subsurface irrigation (SI) on water quality. One study (Campbell et al., 1985) compared differences in nitrate-nitrogen and orthophosphate losses on a sandy soil between a water furrow-irrigation system and a subsurface drainage-irrigation (SI) system. The authors found that SI system reduced overland flow and sediment loss and also resulted in reduced nitrogen loading and potassium concentrations (Fogiel and Belcher, 1991). A Michigan water quality pilot study (Protasiewicz et al., 1988) comparing nutrient and pesticide loads carried to the edge of field in subsurface drain flow between a conventional subsurface drainage system and a subirrigation-drainage system over an 8-month period reported that levels of nitrate-nitrogen and phosphorous carried to the edge of the field by subsurface drain flow were higher for the conventional subsurface drainage system than for the subsurface irrigation-drainage system while levels of potassium and atrazine carried to the edge of field were lower for the conventional subsurface drainage system.

Field trials in Huron County (LeCureux and Booms, 1990c,d; LeCureux, 1991a,b) over the 4-year period 1987-90 showed that subirrigation does not contribute additional amounts of nitrates or pesticides to tile effluent. Some of the data indicated that subirrigation allowed crops to better utilize nutrients, thus reducing the residual amounts of these chemicals being lost in the tile system or in surface runoff. Data from 1988, a low rainfall year, showed that the subirrigated fields released lower levels of nitrates into tile effluent in the fall than the drainage only fields. On the other hand, data from 1989, a more plentiful rainfall season, indicated that both systems released approximately the same level of nitrates into the tile effluent.

Fogiel (1992) monitored the effects of water table management on nutrient and chemical loadings in surface and subsurface runoff and in the soil for 2 years at a field site in Unionville, Michigan. He found that in comparison with a no subsurface drainage (NSD) system, both subirrigation (SI) and conventional drainage (DR) reduced surface drainage outflow and surface drainage orthophosphorus loading for an above average rainfall (AAR) growing season drainage but resulted in similar surface drainage and surface drainage loadings of orthophosphorus during a below average rainfall (BAR) growing season. For both AAR and BAR growing seasons, both SI and DR resulted in increased total flow from the field but in reduced surface drainage loadings of nitrate nitrogen and potassium compared with the NSD treatment. In comparing SI and DR, Fogiel found little difference in effect on surface drainage outflow for either growing season, but that SI increased tile outflow and reduced tile outflow loadings of nitrate nitrogen and orthophosphate phosphorus for the AAR growing season. SI increased potassium tile outflow loading for both seasons. Testing of field samples for the top 0.3 meters of soil for alachlor and nutrients showed no traces of alachlor for any WTMS, but both tile drained treatments were found to have significantly higher orthophosphate phosphorus loadings for the AAR season and the SI treatment had significantly higher orthophosphate phosphorus than did either the DR and NSD treatments for the BAR season. For both growing seasons, the tile drained treatments had significantly higher potassium loadings than the NSD treatment.

To summarize these results, in comparing subirrigation with drainage only, subirrigation results in lower nitrate nitrogen losses in surface runoff and in the tile effluent and in higher potassium and atrazine loadings in the tile effluent, regardless of seasonal rainfall. Subirrigation results in higher phosphorus soil concentrations in low rainfall years.

Because current scientific understanding of the effects of drainage and subirrigation on water quality is limited and inconclusive, a research site has been established in the Saginaw Bay area to study these effects. Both nutrient and pesticide sampling of tile effluent, and surface runoff, and soil will provide additional data to judge the environmental effects of water table management.

2.3. Economic Analyses of Irrigation

There is a large body of literature on economic analyses of irrigation in general. These can be divided into those that deal with irrigation application strategies under a given irrigation system and those that deal with the investment decision concerning which irrigation system to install given several choices. For the present analysis, the irrigation investment literature is most relevant.

Because irrigation investment decisions involve a long planning horizon, the economic analyses in general use some form of net present value (NPV) model as the analytical tool for evaluating the profitability of the investment. The objective function ascribed to irrigation managers differs depending on the decision environment. Boggess et al. (1983) performed a review of all the irrigation strategy analyses, including investment strategies, reported in professional journals to determine what specific objectives were ascribed to the irrigation manager and how the issue of variability in the decision environment shaped the specification of the objective function. They summarized the key sources of variability addressed in the studies as follows:

(1) Variability in aboveground conditions, which include plant capabilities, soil cultivation practices, level of weed control, wind conditions, degree of solar radiation, rainfall quantity and timing, humidity and temperature.

(2) Variability in below ground conditions, including rooting depth and density, nutrient movements and levels, water holding and hydraulic features of the soil, proximity to ground water, and infiltration rates.

(3) Variability of product price.

(4) Variability in marginal costs of irrigation water, including fuel and labor costs and cost differences related to the design of the irrigation system.

(5) Variability of institutional features of the water supply system, including rules affecting when water can be pumped, how much can be diverted, and when it can be used at all.

They concluded that yield variability as influenced by above and below ground conditions has received the brunt of attention in the literature. Yet they were surprised by the fact that only three studies (Yaron and Strateener, 1973; Harris and Mapp, 1980; and Boggess et al., 1981), of 52 studies reviewed, presented estimates of the variance of profits stemming from yield variability associated with various strategies and only two of those three (Yaron and Strateener, 1973; Boggess et al., 1981) posited that profit maximization subject to minimum variance of profits represents a credible goal of irrigation managers. The other studies used single-dimensional decision criteria to determine optimal irrigation strategies. The objective functions included yield maximization, profit maximization, water use minimization, yield maximization given a fixed quantity of water, etc.

To illustrate the diversity of approaches emphasized by Boggess et al. (1983), two studies are presented below. The Wilson and Eidman study (1983) is a straight-forward investment analysis that assumes the goal of the irrigation manager is to choose the irrigation strategy that maximizes profits under conditions of certainty. It assumes known and fixed financial parameters and uses an average yield differential between irrigated and nonirrigated production. The Boggess and Amerling study (1983) begins with the assumption that the goal of an irrigation manager is to choose a production strategy that reduces income variability. It therefore tries to assess the impact of variations in weather patterns and the associated variability in yield differentials between irrigated and dryland production on the profitability of irrigation investments in humid regions.

Wilson and Eidman (1983) used the results of a survey of irrigators in the southwest and south central regions of Minnesota to perform a financial analysis of investing in a center pivot irrigation system for several different soils found in the two regions. The impetus for the study was that farmers in the aftermath of the 1974-76 drought installed irrigation systems without having specific information about the financial profitability of irrigation for their soils.

The authors obtained information from irrigators for both irrigated and nonirrigated yields of corn and soybean and developed a yield differential model for predicting corn yields. They used this information to analyze the profitability of investing in a center pivot irrigation system for different soils using an after-tax net present value model. In their analysis, they abstracted from all potential sources of risk, assuming an average yield differential over the 15-year planning horizon, assuming fixed investment costs, fixed crop prices, and fixed pumping costs each year. They found that irrigation is profitable on soils with a moderate available water capacity (lighter soils) but is not profitable (assuming a 12% desired after-tax rate of return) on high and very high available water capacity soils (heavy soils). The lower profitability on the heavier soils was directly related to the lower yield differential between dryland and irrigated yields on these soils.

Boggess and Amerling (1983) investigated the importance of the pattern of weather variability on irrigation investment decisions in humid climates. They argued that irrigation investment decisions in humid climates differ markedly from those in arid climates because of the sensitivity of net present value (NPV) to the particular weather sequence over the economic life of the investment. They were able to capture this particular feature of the investment decision by using Monte Carlo techniques to generate probability distributions of NPVs. They used a simulation model to generate dry-land and irrigated crop yields based on a 17-year time series of historical weather data and incorporated the results from the simulation model into a net present value analysis. For two different soil groups and three different crops (corn, peanuts, and soybeans), they studied the profitability of four alternative irrigation investment options, two based on a center pivot system and two based on a traveling gun irrigation system. They found that the profitability of the systems over a dryland production system differed by crop and by soil type. For a sandy soil, only the low pressure center pivot (LPCP) irrigation system had a positive expected NPV for all three crops[1] and peanuts

[1] NPV figures were reported as the additional benefits of investing in irrigation as compared to dryland production of the same crop.

was the only crop for which all four irrigation systems had positive expected NPVs. For a sandy loam soil, none of the irrigation systems had a positive expected NPV.

Sensitivity analysis of the NPV results to marginal tax rate, inflation rate, product price, and yield response for the LPCP system revealed that the expected NPV of investing in irrigation is relatively more sensitive to yield response and output prices than to the other parameters. The authors found that of the three crops studied, the NPV results for corn, which had the lowest per-unit value of the three crops, were the most sensitive to yield response. This finding highlights the fact that the assumed level of product price can have a significant impact on the NPV results and that sensitivity analyses should be done for a range of product prices.

For the sandy soils, the authors compared the cumulative distribution functions (CDFs) of NPV for the different investment options to determine stochastic dominance. They found that within crops, the systems could be ordered by first degree stochastic dominance (FSD), with the LPCP system dominating the others. This particular result occurred because all the irrigation systems were assumed to produce equal yield results but involved differing investment costs. In comparing the CDFs of NPVs across crops on both soil types for the dominant irrigation system, the LPCP system, they were able to set priorities for irrigating different crops given either soil type. Thus they found that on sands, peanuts dominate corn by FSD and both dominate soybeans by FSD. On sandy loams, they found that corn dominates both soybeans and peanuts by FSD, while soybeans dominate peanuts by SSD.

2.4. Economic Evaluations and Studies of Yield with Subirrigation

Unfortunately, literature on the economics of subirrigation is limited. A thorough literature search revealed no studies done by economists on subirrigation. Available economic and yield studies fall into two categories: Those done by extension agents and engineers using actual data from field trials and those done by engineers using simulated data. The studies will be summarized below based on this distinction.

Before going into the results of specific economic analyses of subirrigation, some general information is provided first to clarify basic cost considerations in water table management systems. For any drainage (DR) or subirrigation (SI) system, cost effectiveness depends on the crop, soil, topography, climate, water supply (for SI), and degree of management. The two main expenses involved in installing and operating a water table management system are the costs of providing a water supply and of installing underground tiles. Tiles must be laid for both DR and SI systems, but for effective subirrigation, the tile spacing is often narrower. The tiles and water supply costs are very site specific and can vary as much as 300%. Evans et al. (1988) give a very detailed analysis of costs associated with different drain spacings, water sources, control systems, and pumps for North Carolina. The cost of a water supply varies greatly by water source. For a surface water source such as a pond, stream, lake, etc., the initial investment cost is limited to the pump and electricity hookup charges. If a surface water source is not available, the SI investment costs include the well installation costs and higher pump investment costs. In addition, operating costs for a well water source are higher than for a surface water source. In the Huron County studies presented below (LeCureux and Booms, 1990a-d; LeCureux 1991a,b) electricity costs for surface pumping ranged from $4.19 to $5.60/acre, while those for deep well pumping ranged from $9.60 to $12.35/acre, a difference of $5.41 to $6.75/acre. Pump depreciation and interest costs for surface pumping were reported as $15.35/acre based on a 7-year depreciation period and 12% interest. The same costs for deep well pumping were $32.57/acre. The combined difference between these system costs for a well water source and a surface water source is as high as $24/acre.

The reality of these cost differences is evident in the water source use patterns of agricultural producers in the Saginaw Bay area. A 1988 subirrigation inventory survey by Belcher and Wood (1990) found that 90% of survey respondents used a surface water source such as a stream or river (30%), a ditch (43%), or a pond (17%). Only 13% of the respondents reported using a well as their water source.[2] That same inventory revealed that 69% of the subirrigation systems were originally drainage only systems that were retrofitted for subirrigation.

From the above, it is clear that any economic analysis must clearly specify the underlying assumptions about costs and the characteristics of the site. More general conclusions can be drawn from economic analyses if sensitivity analyses of key assumptions are performed to give a better idea of the range of outcomes possible when a key parameter is changed.

2.4.1. Field Studies

2.4.1.1. Yield Analyses

Michigan-specific yield data for subirrigation is available through two unpublished theses (Fogiel, 1992; Belcher, 1990). Fogiel's study evaluated the effect of subirrigation

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[2] Some respondents used both a well and a surface water source so the total does not equal 100%.

on corn yield at a field site in Unionville in Tuscola County during 1990 and 1991. All management inputs except water table management were the same for three treatments: a subirrigated treatment (SI), a drainage-only treatment (DR), and a no-drainage treatment (ND). The results show that SI yields were 9% higher than DR yields and 17% higher than ND yields in 1990, a year where rainfall was 32% above the 30-year average rainfall for the site. In 1991, a year where rainfall was 52% below the 30-year average, the SI yield was 58% higher than the DR yield and 76% higher the ND yield. Fogiel's results show that subirrigation produces a significant yield benefit over no drainage in both wet and dry years, with the largest increase derived in dry years, and produces a modest yield benefit over drainage only in wet years, but a substantial yield increase in dry years.

Belcher (1990) studied the yield effect on corn and soybean of varying the water table level at two field sites: St. Johns in Clinton County and Bannister in Gratiot County. At the Bannister site, which has a Ziegenfuss soil, subirrigation tile laterals were spaced 20-, 40-, and 60-ft apart and at the St. Johns site, which has a Wasepi soil, they were spaced 40-, 56-, and 79-ft apart. Corn yield results at the Bannister site for 1986, the first year after the system was installed, at the different spacings and water table depths ranging from 38 to 95 cm, did not show a high correlation between water table depth and yield nor were there noticeable yield differences between the different tile spacings. These results could have been due to the fact that the soil at the site had been disturbed the previous season when the subirrigation system was installed.

In 1987, water table depths were allowed to vary more significantly than in 1986 (from 48 to 158 cm) and there was a more noticeable treatment effect between the different water table depths at the same tile spacing. At the 20-ft tile spacing, the corn yield was 226 bushels/acre (bu/acre) at a water table depth of 48 cm compared with a yield of 138 bu/acre at 63 cm and 172 bu/acre at a 144 cm water table depth. At the 60-ft tile spacing, yields increased steadily with decreases in the water table depth. At a depth of 123 cm the yield was 138 bu/acre, at 96 cm it was 156 bu/acre, and at 82 cm it was 200 bu/acre.

The St. Johns results are similarly mixed for 1987, the year following installation of the system. However, in 1988, a very dry year, the relative yields increased at each tile spacing as the water table depth was raised. At the 40-ft tile spacing, corn yields rose from 116 bu/acre to 166 bu/acre as the water table depth was raised from 112 cm to 70 cm. Similarly, at the 80-ft tile spacing, relative yields rose from 116 bu/acre to 182 bu/acre as the water table depth was raised from 112 cm to 71 cm.

Other field studies of yield for subirrigated crops outside of Michigan are available and provide useful information for comparative purposes. Most of these studies use the results of field data from other researchers to validate the DRAINMOD simulation model (Hardjoamidjojo et al., 1982; Hardjoamidjojo and Skaggs, 1982).

Hardjoamidjojo et al. (1982) studied the effect of drainage, including surface drainage, tile drainage, and a combination of tile and surface drainage, on corn yields under excessive soil water conditions. Their findings are important because they highlight the fact that improving drainage alone on poorly drained fields greatly improves corn yields.

In reporting their results, Hardjoamidjojo et al. used the concept of relative yields. This concept warrants explanation here because it will appear again when results of simulation studies are summarized. Relative yield in percent terms (YR) is the actual measured yield (Y) divided by the potential yield (Y_o): $YR = Y/Y_o \times 100$.

The potential yield can be either the highest yield obtained in a particular field trial or it can be the yield goal set based on current technology and given perfect growing conditions. The concept of relative yield is used to eliminate the effects of factors other than the drainage treatment effects when comparing yields across trials and across years.

Hardjoamidjojo et al. (1982) ran field trials in Ohio under excessive soil water conditions from 1962-64, 1967-71, 1976-79 and compared the effect of no drainage, surface drainage only, tile drainage only, and tile plus surface drainage treatments on corn yields. Excess water was the only stress the corn plants were exposed to. Under these conditions relative yields improved consistently from a situation of no drainage, to surface drainage, to tile drainage, to tile plus surface drainage. With tile plus surface drainage, relative yields were greater than 90% in 8 out of the 13 years.

2.4.1.2. Economic Analyses

In Michigan several economic studies of subirrigation on row crops have been done by an extension agent, Jim LeCureux, working with farmer cooperators in the Saginaw Bay area as part of the SBSD project. These Huron County studies are published in two volumes (D'Itri and Kubitz, 1990 and 1991) and report the results of field trials from 1987-90. The crops evaluated include corn, soybean, sugar beets, and dry beans. LeCureux evaluated subirrigation for crops singly and as part of a rotation scheme (LeCureux and Booms, 1990a-d; LeCureux, 1991a,b). In addition, two studies of the economics of subirrigation on alfalfa have also been done in the Saginaw Bay area (Auernhamer and Belcher, 1990; Protasiewicz and Auernhamer, 1991).

Because of the relevance of the Huron County studies to the present study, a fairly comprehensive accounting is made of the approach taken in both the trials and the economic analysis of the trials. The results of the 1987-90 field trials are summarized in Tables 2.1 - 2.5. In order to present as much information as possible in the tables, abbreviations have been used extensively. These are summarized below.

Abbreviation	Significance
Mgt	Management Strategy
Drain Space	Spacing between drainage tiles
SI Adv	Difference between results of the subirrigated treatment and the companion drainage only treatment for the same tile spacing
CN	Corn
SB	Soybeans
NB	Navy beans
SBT	Sugar beets
WH	Wheat
SI	Subirrigated
HW	High Water Table Goal (close to soil surface)
MW	Medium Water Table Goal
LW	Low Water Table Goal (further from soil surface)
DR	Drainage only
R30	30-inch crop row spacing
R15	15-inch crop row spacing

1987 Field Trial Results (See Table 2.1)

The 1987 field trials (LeCureux and Booms, 1990a) evaluated the effect of subirrigation on corn yields at two sites where the tile spacings were 25 feet on a Kilmanagh soil (Site 1) and 60 feet on a Shebeon/Kilmanagh soil (Site 2). At both sites subirrigated treatments (SI) were compared to drainage only treatments (DR).

At Site 1, two water table levels were tested for the subirrigated plot and alternate yield goals of 200 bu/ac, 180 bu/ac, and 160 bu/ac were set for the irrigated zones. A single yield goal of 160 bu/ac was set for the DR treatment. Plant populations and fertilizer levels varied by yield goal. The logic behind establishing three different yield goals for the subirrigated zone and a single lower yield goal for the drainage only zone is that higher yields can be expected for the subirrigated plots because water is not a limiting factor. Thus, separate production functions are assumed for the different treatments. At Site 2, a single yield goal of 180 bu/acre was established for both treatments.

Yield results for the different zones at both sites are summarized in Table 2.1.

TABLE 2.1: Summary of Yield Results for 1987[3]

Site	Crop	Mgt	Drain Space	Yield Goal	Actual Yield	SI Adv
1	CN	SI	25			
		HW		200	174	59
				180	170	55
				160	155	40
		LW		200	176	61
				180	171	56
				160	160	45
		DR	25	160	115	
2	CN	SI	60	180	121	0
		DR	60	180	121	

(Source: LeCureux and Booms, 1990a)

Because the 1987 economic analyses do not include depreciation costs or interest for the pumping equipment and other control structures necessary for subirrigation, net revenue figures are not included in Table 2.1. These costs were included in all subsequent Huron County economic analyses and results are therefore presented and compared for the later analyses.

The results at Site 1, where a well water source was used, show that in a year where the rainfall is unevenly distributed, such as 1987, subirrigation produced a yield difference of as much as 62 bu/acre over drainage only.

[3] Seasonal rainfall for 1987 at Site 1 was 16.25 inches and at Site 2 it was 14.65 inches. Normal seasonal average rainfall for Huron County is 17.3 inches.

At Site 2, the surface water source used for subirrigation could not provide adequate water to subirrigate the test plot. In addition, at the 60-ft tile spacing it was not possible to maintain a uniform water table in the subirrigated field. Under these conditions, there was no yield difference between the partially subirrigated plot and the drainage only plot.

1988 Field Trial Results (See Table 2.2)

The second year of field trials, 1988, was also a dry year in Huron County. Corn trials were repeated at Site 1 and Site 2 (although on different plots) and a sugar beet trial was run at a third site, Site 3, which also had a Kilmanagh soil (LeCureux and Booms, 1990b-d). At Site 2, a different field from the 1987 one was chosen for the field trial. In this field, the tiles were spaced at 25 feet instead of 60 feet. Instead of a subirrigated and drainage only comparison, this time three water table depths were compared: 12-inch (HW), 18-inch (MW1 and MW2), and 35-inch (LW1 and LW2) and three yield goals (160, 180, and 200 bu/ac) were established. One area of the low water table field had water levels that remained at 48 inches and yields from this plot are considered equivalent to a drainage only treatment for comparisons.

The gross margin analysis for subirrigation included annual principal and interest payments on the pump installation and material based on 12% interest over 7 years and annual per acre electrical charges for pumping water. Seed and fertilizer costs for subirrigated corn were higher than for the drainage only case using the same assumption as before that a lower yield goal needs to be set for the drainage only treatment.

The results of the trials and the net margin analysis are summarized in Table 2.2. For the economic analysis, LeCureux compared the HW SI treatment with the DR treatment and found a yield advantage of 47 bu/acre and a net revenue advantage of $90/acre for the subirrigated corn. Although LeCureux did not do an economic analysis of the different water table level management schemes, the yield results show that there was a difference in yields due to the variation in water table levels. Yields for the field where the water table averaged 12 to 18 inches were 30 bushels higher than yields for the 35-inch water table field. However, there was very little difference in yields between the 12- and 18-inch water table treatments.

At Site 1 alternate water table levels were established in the subirrigated zone and a drainage only zone served as a control. All treatments had 25-ft tile spacings. A yield goal of 160 bu/acre was set for the drainage only treatment and less fertilizer and seed were used. A 180 bu/acre yield goal was set for the subirrigated plots.

Yield results show no significant yield difference between high and low water table zones, but a significant 71 bu/acre difference between the subirrigated treatments and the drainage only treatment. The economic analysis shows a $72/acre benefit to subirrigation (Table 2.2). The smaller gross margin at Site 1 compared with Site 2, where the yield difference between SI and DR corn was smaller than at Site 1 was due to the higher cost of well water compared with surface water. In both cases, however, the results show that no extra benefit is derived from maintaining too high a water table.

A sugar beet trial was run at Site 3. Two zones with 60-ft and 30-ft tile spacings were divided into subirrigated and drainage only plots. As with the previous trials, the subirrigated treatment received different levels of inputs (high/low nitrogen and high/low plant populations) to reflect differing yield goals, while the drainage only treatment received only the lower level of inputs (low nitrogen/low plant population). A summarized version of the results is presented in Table 2.2.

In his economic analysis, LeCureux compares the yields and net revenues of the SI and DR treatments for the 30-ft tile spacings and reports a $158.48/acre difference in net revenue in favor of the subirrigated treatment.

In the published results, LeCureux notes that there is a difference in yields between the 30-ft and 60-ft tile spacings for both the subirrigated and drainage only plots (Table 2.2). He does not, however, evaluate the economic benefit of splitting the tiles. In Michigan, many farmers are already "splitting tiles," i.e., decreasing the distance between drainage tiles, to benefit from the increased yields of improved drainage.

TABLE 2.2: Summary of Field Trials and Economic Analyses for 1988[4]

Site	Crop	Mgt	Drain Space	Yield Goal	Actual Yield	SI Adv	Net Rev[5]	SI Adv
1	CN (WH)[6]	SI	25					
		HW		180	161	71	$174	$72
		LW		180	161	71		
		DR		160	90		$102	
2	CN (WH)	SI	25					
		HW			166	47	$273	$90
		MW1			164	45		
		MW2			164	45		
		LW1			133	14		
		LW2			132	13		
		DR	25	160	119		$183	
3	SBT (NB or SB)	SI	60		22.1	6.6		
			30		24.5	6.4	$487	$158
		DR	60		15.5			
			30		18.1		$329	

(Source: LeCureux and Booms, 1990c,d)

[4] Seasonal rainfall in 1988 at Site 1 was 16.25 inches, at Site 2 it was 10.02 inches, and at Site 3 it was 11.3 inches.

[5] Corn price = $2.50/bu. Sugar beet price = $31.00/ton.

[6] Refers to the crop planted previously at the site.

Using the yield and cost data provided by LeCureux, a rough gross margin analysis of the benefit of splitting the tiles for this trial can be made for both the subirrigated and drainage only cases. The retrofit calculations were made using an annual principal and interest payments figure of $39.12 on tile and material. This figure is based on 12% interest over 15 years (LeCureux and Booms, 1990c, p.235). Using this figure, the benefit to splitting the tile for the subirrigated treatments is $52.68 and for the drainage only treatment is negative $17.92 (Table 2.3A, 2.3B).

TABLE 2.3A: Benefit to Splitting Tiles for Sugar Beet - SI Treatment

ECONOMIC INFORMATION: SITE 3		
Treatment	30-ft tile space SI	60-ft tile space SI
Yield	24.5 tons	22.1 tons
Gross Income ($31/ton)	$759.50/acre	$658.10/acre
EXPENSES ($):		
Hauling ($4/ton)	$ 98.00	$ 88.40
Tile	$ 39.12	
TOTAL EXPENSES	$137.12	$ 88.40
GROSS MARGIN	$622.38	$569.70
DIFFERENCE: $ 52.68		

(Source: LeCureux and Booms, 1990c,d)

TABLE 2.3B: Benefit to Splitting Tiles for Sugar Beet - DR Treatment

ECONOMIC INFORMATION: SITE 3		
Treatment	30-ft tile space DR	60-ft tile space DR
Yield	18.1 tons	15.5 tons
Gross Income ($31/ton)	$ 516.10/acre	$ 480.50/acre
EXPENSES ($):		
Hauling ($4/ton)	$ 72.40	$ 62.00
Tile	$ 39.12	
TOTAL EXPENSES	$ 115.52	$ 62.00
GROSS MARGIN	$ 400.58	$ 418.50
DIFFERENCE: ($ 17.92)		

(Source: LeCureux and Booms, 1990c,d)

This simple example shows that under the climatic, management, and cost conditions prevailing in 1988, splitting tiles for drainage only when growing sugar beets was not economically attractive. At the same time is shows that splitting the tiles for subirrigation under 1988 conditions was profitable.

1989 Field Trial Results

Beginning in 1989, LeCureux extended his analysis to include the effects of a rotation (LeCureux, 1991a,b). Agricultural producers in the area rotate some combination of corn, dry beans, soybeans, and sugar beets. LeCureux tried to capture the significance of this practice for the economic viability of subirrigation.

In order to utilize all the available yield data from the various trials, LeCureux averaged the yield and net revenue results of all the 1987 and 1988 corn and sugar beet trials with the results of the 1989 corn, soybean, navy bean, and sugar beet trials (to be discussed below) and then compared the subirrigation and drainage only yield and net revenue figures. For the corn, beet, soybean, navy bean rotation, he reports an average benefit to subirrigation of $24.37/acre.

This approach utilizes all the available data, but it does not give an accurate picture of the benefit to subirrigation under rotation at the level of a single field. From the 1988 and 1989 field trials, data were available for a corn - soybean rotation at Site 2 for the same field and on a sugar beet - corn rotation at Site 3 for the same field. These data can be used to consider the economic benefit to subirrigation under a rotation on the same field. This approach will be illustrated below after the results of the 1989 field trials are summarized.

One other issue that LeCureux addressed in analyzing the 1987-89 results of the various trials was whether subirrigation reduces year-to-year yield variability for the different crops. He again compared results from all the field trials at the different farms. Again, ideally, an analysis of variability should be done for the same field with the same tile spacing. LeCureux did not have a long enough data series to make such an analysis.

In 1989, LeCureux ran three field trials at Site 2: sugar beets, soybeans, and navy beans. The sugar beet trial was run in a field with 30-ft tile spacings that was subirrigated and in a field with 60-ft tile spacings that had both a subirrigated and drainage only treatment. All plots received the same level of inputs.

The results of the yield and economic analysis are presented in Table 2.4. Comparing results for the 60-ft tile spacing, the subirrigated treatment had a $33.05 net benefit over the drainage only treatment. Comparing the 30-ft SI treatment and the 60-ft SI treatment to evaluate the benefit of splitting the tile for subirrigation, we see that the benefit is only $2/acre. Using cost data from the 1988 analysis, where costs for splitting tiles were reported as $39.12/acre based on 12% interest over 15 years, it is clear that under 1989 conditions it the economic benefit of splitting the tiles for subirrigation is negative.

Because a 30-ft drainage only treatment was not included in the trial, we cannot evaluate the benefit to splitting tiles for drainage only. This would be a useful comparison, however, because some of the yield benefit of the 30-ft SI treatment over the 60-ft DR treatment might actually be attributable to improved drainage alone in moving to a smaller drain spacing. For sugar beets, the yield benefit of the 30-ft SI (subirrigated) treatment over the 60-ft DR (drainage only) treatment was less than 2 tons. Comparing the economic results of the 30-ft SI treatment and the 60-ft DR treatment, a benefit of $34.88 is gained from <u>both</u> splitting tiles and subirrigating. As mentioned above, if the costs of splitting tiles are taken into consideration, the benefit of splitting tiles and retrofitting a drainage only system for subirrigation is negative. These conclusions, of course, depend on the price of beets, the level of management, and the rainfall for the 1989 season. Rainfall in 1989, while still below average, was more plentiful and much more evenly distributed than in 1987 or 1988. The 1988 beet trial at Site 2 showed a greater than 6 ton yield increase due to subirrigation, whereas in 1989 the yield increase was less than 2 tons. This example illustrates how sensitive the economic benefit to subirrigation is to seasonal rainfall, crop price, and crop grown.

The 1989 corn trial at Site 3 was run on the same field as the 1988 sugar beet trial. As before, both the 60-ft tile spacing and 30-ft tile spacing fields were divided into subirrigated and drainage only plots. The management scheme in this trial included using different corn varieties to evaluate sensitivity of results to plant variety and applying different nitrogen levels to test sensitivity of yields to nitrogen level. The management, yield, and net revenue results are summarized in Table 2.4. Only the low nitrogen regime was applied to the drainage only treatment. Yield differences by plant variety and level of nitrogen were insignificant.

While the yield results show a positive benefit to subirrigation in all cases, they also show a negative benefit in terms of net revenue. Any increase in yield was offset by the additional costs of production (pumping charges and equipment depreciation, additional fertilizer and seed costs) associated with the subirrigated treatments. In this trial, the largest net revenue was for the 30-ft tile spacing DR treatment. As in the beet trial for 1989, these results demonstrate that the economic benefit to subirrigation is largely dependent on seasonal rainfall. In good rainfall years, subirrigation produces little or no economic benefit, whereas in poor rainfall years, the benefit can be substantial.

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TABLE 2.4: Summary of Field Trials and Economic Analyses for 1989[7]

Site	Crop	Mgt	Drain Space	Yield Goal	Actual Yield	SI Adv	Net Rev[8]	SI Adv
2	SBT (NB)	SI	60		24.02	1.51	$717	$33
			30		24.07		$719	
		DR	60		22.51		$684	
2	SB #1[9] (CN)	SI	25					
		R30			40.2	0.4	$147	($17)
		R15			40.4	0.3	$144	($18)
		DR						
		R30			39.8		$164	
		R15			40.1		$162	
	SB #2 (CN)	SI						
		R30			38.6	0.9	$135	($15)
		R15			38.4	(0.5)	$129	($23)
		DR						
		R30			37.7		$150	
		R15			38.9		$152	
2	NB #1 (CN)	SI	25					
		R30			20.0	(0.9)	$390	($37)
		R15			21.6	(0.6)	$416	($34)
		DR						
		R30			20.9		$427	
		R15			22.2		$450	
3	CN #1 (SBT)	SI	60	200	180.6	27.1	$172	$16
					175.1	21.6	$151	($ 5)
					170.1	16.6	$154	($ 2)
			30	200	183.6	15.2	$174	($11)
					182.3	13.9	$168	($17)
					178.3	9.9	$167	($18)
		DR	60	200	153.5		$156	
			30	200	168.4		$185	
	CN #2 (SBT)	SI	60	200	158.5	3.3	$127	($36)
					173.6	18.4	$156	($ 7)
					164.1	8.9	$153	($10)
			30	200	178.7	14.3	$161	($17)
					180.6	16.2	$168	($10)
					171.4	7.0	$168	($10)
		DR	60	200	155.2		$163	
			30	200	164.4		$178	

(Source: LeCureux, 1991a)

[7] Seasonal rainfall in 1989 at Site 2 was 12.46 inches and at Site 3 it was 10.42 inches.

[8] Corn Price = $2.30/bu. Sugar Beet Price = $40.00/ton. Soybean Price = $5.75/bu. Navy Bean Price = $24.00/cwt.

[9] Refers to a specific variety when more than one variety was used in the trial.

The 1989 soybean and dry bean trials at Site 2 can be briefly summarized as follows: Soybeans were grown on a 25-ft tiled field where half the field was subirrigated (SI) and the other half drained only (DR). Alternative management schemes including different plant varieties and row spacings were replicated on both the SI and DR plots. Statistical analysis of yields between SI and DR plots showed no significant difference at the 5% significance level. Neither was there a yield difference associated with the different row spacings. There was a slight yield difference between the two varieties. As was the case with beets and corn in 1989, the drainage only treatment had the highest economic return because of lower input costs.

Navy beans were grown under the same management systems used in the soybean trial. Statistical analysis showed the drainage only yield to be higher than the SI treatment at the 5% significance level. The economic analysis showed the DR treatment to be more profitable by $33.85 to $36.53, depending on the row spacing.

Now turning to the issue of the economic analysis of subirrigation under a rotation for the same field, available data for yield and net revenue for Site 2 and Site 3 are used to perform a basic economic analysis. For each site, 2 years of data are available. By taking the figures for the benefit to subirrigation (SI advantage) for each crop for each year and averaging them, the economic benefit of subirrigation for that specific rotation can be calculated.

At Site 2, the SI advantage for corn in 1988 was $90/acre and for soybeans in 1989 was negative $18.25/acre (the average of all SI advantage figures in Table 2.4). This translates into an average annual per acre benefit to subirrigation for a corn - soybean rotation of $36/acre.

At Site 3, the SI advantage for sugar beets in 1988 for the 30-ft tile spacing was $158. In 1989, the average SI advantage for corn in the 30-ft tile spacing field was negative $10. This translates into an average annual per acre benefit to subirrigation for a sugar beet - corn rotation of $74.

1990 Field Trial Results

The 1990 field trials included sugar beet and corn trials at Site 2 and a navy bean trial at Site 3 (LeCureux, 1991d).

The management scheme for the sugar beet trial consisted of two treatments, an SI treatment and a DR treatment, on a field with 25-ft tile spacings. Both the SI and DR plots received the same levels of inputs. Rainfall was above the average for the season.

As can be seen in Table 2.5, the SI treatment yielded 1.8 more tons than the DR treatment and had a net revenue advantage over the DR treatment of $47.93/acre.

The corn trial followed the same management procedure as that used in the 1989 beet trial at Site 2. The 30-ft spacing field was subirrigated and the 60-ft spacing field had both a SI and DR plot. Two varieties of corn were planted to evaluate yield differences. All plots received the same level of fertilizer, seed, herbicides and insecticides. The yield results for the two varieties of corn varied only slightly. Highlighting the results for only one of the corn varieties (Pioneer 3573), the results show the 60-ft SI treatment had a yield of 151.6 bu/acre and a gross margin of 150.29 while the 60-ft DR treatment had a yield of 142.3 bu/acre and a gross margin of $155.67. The higher SI yield was not high enough to offset the higher production and fixed costs associated with subirrigation, so the DR treatment had a gross margin $5.38/acre higher than the SI treatment in 1990.

The procedure for the navy bean trial was the same used on the corn trial at Site 3 in 1989: 30-ft and 60-ft tile spacings with both an SI and DR treatment on each spacing. Each plot was planted with three different varieties to determine if there were substantial yield differences due to plant variety. Rainfall was above average for the season and only a limited amount of water needed to be applied through subirrigation to the SI field.

The SI navy beans, regardless of variety or tile spacing, yielded better than the DR navy beans. The largest yield difference was 7.3 cwt/acre for the 30-ft spacing with the Wesland variety. This treatment also had the largest difference in gross margin, $107/acre, over the DR treatment. This result is the opposite of what we saw with corn, where under good rainfall, yield differences between SI and DR treatments were minimal. It implies that navy beans may benefit more from subirrigation in general, showing less variability in response due to weather than corn does. This highlights an important fact: different crops respond differently to subirrigation under weather variability. Economic analyses of subirrigation under rotation should capture this effect. With this in mind, the economic analysis of subirrigation under rotation is extended by incorporating the 1990 yield and net revenue results for the same sites as above.

Using the same approach applied above, the results are as follows:

At Site 2, the 1988-89-90 corn - soybean - sugar beet rotation had net returns of +$90/acre, -$18/acre, and +$48/acre, for an average annual per-acre benefit to subirrigation of $40.

At Site 3, the 1988-89-90 sugar beet - corn - navy bean rotation on the 30-ft spacing field had net returns of +\$158/acre, -\$10/acre, and +\$77/acre, for an average annual per-acre benefit to subirrigation of \$75.

TABLE 2.5: Summary of Field Trials and Economic Analyses for 1990[10]

Site	Crop	Mgt	Drain Space	Yield Goal	Actual Yield	SI Adv	Net Rev[11]	SI Adv
2	SBT (SB)	SI	25		28.0	1.8	\$929	\$48
		DR			26.2		\$881	
2	CN #1	SI	60	180	151.6	9.3	\$150	(\$6)
	(SBT)		30	180	153.4		\$154	
		DR	60	180	142.3		\$156	
	CN #2	SI	60	180	160.6	8.1	\$167	(\$7)
	(SBT)		30	180	162.6		\$171	
		DR	60	180	152.5		\$174	
3	NB #1	SI	60		25.7	5.9	\$315	\$87
	(CN)		30		25.8	4.3	\$316	\$63
		DR	60		19.8		\$228	
			30		21.5		\$253	
	NB #2	SI	60		24.4	3.8	\$296	\$56
	(CN)		30		25.4	4.2	\$310	\$62
		DR	60		20.6		\$240	
			30		21.2		\$248	
	NB #3	SI	60		21.5	6.1	\$253	\$89
	(CN)		30		21.3	7.3	\$250	\$107
		DR	60		15.4		\$164	
			30		14.0		\$143	

(Source: LeCureux, 1991b)

2.4.2. Simulation Studies

Engineers at North Carolina State University have produced a number of analyses of drainage and subirrigation using a simulation model, DRAINMOD, that has been specifically designed to choose the optimum drain spacing in designing a drainage/subirrigation system (Skaggs, 1981; Hardjoamidjojo and Skaggs, 1982; Hardjoamidjojo et al., 1982, Skaggs et al., 1982; Evans et al., 1988; Murugaboopathi et

[10] Seasonal rainfall in 1990 at Site 2 was 18.55 inches and at Site 3 it was 20.70 inches.

[11] Corn price = \$2.10/bu. Sugar Beet price = \$42.00/ton. Navy Bean price = \$15.00/cwt.

al., 1991). Some of the analyses have focused on the technical aspects of drain spacing and depth for optimum yields (Skaggs et al., 1982; Hardjoamidjojo and Skaggs, 1982) and some have looked at the economic tradeoff between increased cost of reduced spacing between drains and increased yields for drainage and/or subirrigation (Skaggs and Nassehzadeh-Tabrizi, 1983; Evans et al., 1988; Murugaboopathi et al., 1991). The North Carolina studies distinguish between yield benefit due to drainage and that due to a combination of drainage and subirrigation. They will be presented below based on that distinction.

2.4.2.1. Benefit to Drainage

Skaggs and Nassehzadeh-Tabrizi (1983) analyzed optimum drainage using DRAINMOD to simulate corn yields for a 26-year period of North Carolina weather. They used the results of the simulation model in an economic analysis of the effect of drain spacing and surface drainage on long-term average profits for corn for two soil types.

Simulation results showed substantial beneficial effects of subsurface drainage in wet years and more limited beneficial effects in dry years. Delay in planting date alone in one particularly wet year would have resulted in a reduction in yield to 65% of the potential yield even if soil water stresses did not occur during the rest of the growing season.

The maximum average predicted relative yield was 78% of potential and occurred for a drain spacing of 66 feet for good surface drainage and 56 feet for poor surface drainage. At a drain spacing of 328 feet, which is the conventional spacing between drainage ditches in North Carolina, the maximum average predicted relative yield was only 52% of potential (with good surface drainage).

Annual yield results showed that the benefits of drainage are widely variable on a year-to-year basis. As revealed in the Boggess and Amerling (1983) study, it is the particular pattern of this variability that affects the expected net present value. This is not captured in an economic analysis that looks at average yield differences.

Skaggs and Nassehzadeh-Tabrizi tested the sensitivity of their results to weather at a particular location by running the simulations for the same soil and drainage system inputs but with 15 years of weather data from 6 other weather stations in North Carolina. Their results held for the other weather data and the maximum predicted relative yield occurred for drain spacings between 49 and 66 feet in all cases.

The yield and drain spacing results from the simulations were used in the economic analysis to determine the effect of drain spacing and surface drainage on long-term average profits. Net return to land and management for alternative drainage treatments was calculated as average annual gross income minus costs. Costs included annual drainage system costs, which were the initial system costs amortized over estimated useful lifetime and the variable system costs, and corn annual production costs, which included both fixed and variable costs.

The economic results show that average profit is not maximized at the same drain spacing that maximizes yields because of the trade off between increased cost and increased yield of reduced drain spacing. Maximum yield for the poor surface drainage case occurred at a drain spacing of 56 feet, whereas maximum net return was obtained with a drain spacing of 79 feet. With improved surface drainage, the same relationship held, although net returns were maximized at a lower level than for the poor surface drainage case because improved surface drainage costs were relatively high. Skaggs and Nassehzadeh-Tabrizi tested the sensitivity of the results of the economic analysis to several factors. In their analysis, the initial drainage system costs were amortized at an interest rate of 12%. Alternate rates of 10% and 14% were tested in a sensitivity analysis. The results show that while net returns vary depending on the interest rate, the drain spacing required to maximize profit remains the same. Sensitivity analysis of the results to the price of corn also showed that the drain spacings required to maximize net profits for low corn prices were only slightly larger than for the high prices.

The authors also tested the sensitivity of their results to changes in the assumed potential yield of 175 bu/acre, which could be too high or too low for some soils depending on soil fertility, management practices, and weed and insect problems. The authors found that the optimal spacings are not sensitive to the potential yield for the range of conditions considered.

Thus, while interest rate, corn price and assumed potential yield have large effects on net return, they have only small effects on the drainage design required to maximize net returns.

Skaggs and Nassehzadeh-Tabrizi (1983) also considered the influence of drainage on the year-to-year variation in net return. For the period 1950 to 1975, net return was positive in 21 out of 26 years for good drainage as compared to a positive net return in only 11 out of 26 years for poor drainage.

The authors extended this basic analysis of variability to calculate the payoff period for an investment in improved drainage. They stressed that a farmer's ability and or willingness to invest in drainage depends more on the length of time required for the investment to pay for itself. This depends on the size of the initial investment and the increase in profits due to drainage. Using the optimum drain spacing that maximized average profits, they demonstrated that if all profits were used to pay off the initial investment, the drainage system would pay for itself in only three crop years.

Another North Carolina study of yield benefit to drainage only (Hardjoamidjojo and Skaggs, 1982) showed that with the correct drain spacing for drainage only, yields can reach 80% of their potential. Higher yields (up to 20% higher yields) can only be achieved by reducing deficient soil water stresses through subirrigation.

2.4.2.2. Benefit to Drainage/Subirrigation

Because studies have shown that improved drainage alone can dramatically improve corn yields (Hardjoamidjojo and Skaggs, 1982), a clear distinction must be made between benefit to improved drainage and to subirrigation. Evans et al. made this distinction very clear in their analysis of controlled drainage and subirrigation systems (Evans et al., 1988). They used the simulation model DRAINMOD to analyze the effect of different drain spacings on yield for a drainage only base case, highlighting the tradeoff of increased yield from reduced drain spacing and increased tile costs of reducing the drain spacing. For the drainage only base case, they controlled for cost differences based on surface drainage characteristics, providing alternate calculations for both a good and poor surface drainage alternative.

After establishing the base yield and net return figures for improved drainage under good and poor surface drainage conditions, they again used DRAINMOD to analyze yield increases due to controlled drainage, subirrigation/drainage, and center pivot sprinkler irrigation. (Only the subirrigation results will be presented here.) Their cost calculations for subirrigation took into consideration fixed and variable costs for pump and control structures for two alternate water supplies: a deep well and surface water. Fixed costs included depreciation, interest, property taxes, and insurance. Variable costs included repairs and maintenance, fuel, and labor. Their pumping cost calculations for subirrigation reflected the fact that subirrigation is only 75% efficient. 25% of the water pumped is lost through seepage to nonirrigated areas, thus pumping charges were adjusted accordingly.

Production costs were also broken down into fixed and variable costs. Production costs for subirrigation were adjusted to reflect increased nitrogen and harvesting costs associated with a higher yield goal. In this specific example, a yield goal of 130 bu/acre was established for the drainage only simulations and 160 bu/acre for the subirrigation simulations. (The implications of setting alternative yield goals with DRAINMOD will be discussed at length in the methodology chapter).

The simulation results for the alternative scenarios of drainage only and subsurface irrigation/drainage clearly show the tradeoff between increased yields with closer drain spacings and increased system costs. For clarity's sake, only comparisons of the fair surface drainage alternative for each scenario are discussed here (Table 2.6). Results of the good surface drainage alternative are similar.

For the drainage only base case, the highest yield (168.5 bu/ac) was achieved with a drain spacing of 50 ft; whereas the highest net return per acre was for a drain spacing of 75 ft. For the subsurface drainage/subirrigation scenario, the highest yield was for a drain spacing of 33 ft. The highest net return per acre for a well water source was $136.56 at a drain spacing of 50 ft and the highest net return per acre for a surface water source $164.33 at a drain spacing of 50 ft.

TABLE 2.6: Yield and Net Return Results with Fair Surface Drainage

Scenario	Optimum Predicted Yield (bu/acre)	Associated Tile Spacing (ft)	Optimum Net Return per acre ($/ac)	Associated Yld / Tile Spacing (yld/sp)
Drainage Only	135.6	50	$135.25	134.6/75
Subirrigation				
Well	168.5	33	$136.56	162.9/50
Surface	168.5	33	$164.33	162.9/50

(Source: Evans et al., 1988)

To establish the additional benefit to subirrigation, the highest predicted net return for subirrigation was compared with the highest predicted net return for the drainage only case. Using this criterion, the benefit of subirrigation over drainage only depends on the water source. Whereas subirrigation is only marginally more profitable than drainage when a deep well is used as the water source, it can boost average profits by $29.08 per acre when a surface water supply is available. These results show that the cost of the water source can be an important factor affecting profits with subirrigation.

The authors conclude that for the conditions assumed, subirrigation would be the most profitable choice. But they also raise the point that since the net profit with subirrigation is only slightly higher than that with conventional subsurface drainage, some farmers might not want to take the risk of the additional capital outlay.

To address this issue of risk, Evans et al. (1988) considered year-to-year variation in profit over a 10-year period for alternative drain spacings in a conventional drainage system compared to several alternative subirrigation systems which varied by drain spacing and water source (surface water versus ground water). After determining the tile spacing that gave the highest long-term average profit for each option, the authors found that conventional subsurface drainage provided the most profit for a continuous corn production system, but it also had the highest loss in one year out of the ten.

Subirrigation provided the most consistent year-to-year profit. A net profit was predicted every year. The authors concluded that from the standpoint of stabilized farm income, subirrigation might be the most desirable option, but from the standpoint of long-term average profit, subsurface drainage might be optimal.

Murugaboopathi et al. (1991) extended the above analysis to evaluate the sensitivity of results to soil type and to evaluate the impact on optimum drain spacing and on optimum net returns of including soybeans in a corn - soybean rotation. The economic analysis was conducted to determine the drain spacing that gives the maximum net return to land and management for the corn - soybean rotation.

The procedure used mimics the Evans et al. (1988) study in almost all respects, with the exception that Murugaboopathi et al. did not include a controlled drainage or sprinkler irrigation scenario, they used a longer period of weather data (37 years), and they included much more detailed breakdown of the pumping system characteristics necessary for alternative drain spacings.

As with the previous study, to simplify matters, only the results for the fair surface drainage alternative for one of the soil types (Table 2.7 and Table 2.8) are presented here. Results for the good surface drainage case and for the other soil evaluated are quite similar to those presented below.

TABLE 2.7: Results for Corn for a Rains Soil: Fair Surface Drainage

Management System	Optimum Predicted Yld (bu/acre) and YR(%)[12]	Associated Tile Spacing (ft)	Optimum Net Return ($/ac)	Associated Yld / Tile Spacing (yld / sp)
Drainage Only	130.7 75%	50	$70.89	126 / 80
Subirrigation	168.7 96%	33	$111.89	165.2 / 50

(Source: Murugaboopathi et al., 1991)

TABLE 2.8: Results for Soybeans for a Rains Soil: Fair Surface Drainage

Scenario	Optimum Predicted Yield (bu/acre) and YR(%)	Associated Tile Spacing (ft)	Optimum Net Return per acre ($/ac)	Associated Yld / Tile Spacing (yld / sp)
1. Drainage Only	61.6 88%	50	$132.22	59.5 / 80
2. Subirrigation	67.2 96%	33	$122.59	61.6 / 66

(Source: Murugaboopathi et al., 1991)

For the drainage only treatment, the maximum average relative corn yield was 75%. Drought stresses prevented the relative yield from reaching 100% of the potential yield. For the SI treatment, reducing drought stresses allowed corn yields to reach 96% of potential. The yield results also show that the maximum relative corn yield with subirrigation is obtained at a narrower drain spacing (33 ft) than with drainage only, where the maximum relative yield is obtained at 50 ft.

For soybeans, there is much less difference between the maximum average relative yield for SI and DR. With DR, soybean relative yield can reach 88% of potential, compared to 78% for corn. These results imply that soybeans are much less responsive to subirrigation than is corn.

[12] YR (%) is the relative yield.

The economic analysis revealed an important issue. In looking only at the corn results, the benefit to subirrigation was $41/acre. Subirrigation increased profits by 57.7% over drainage only. This is a very impressive gain. But in looking at the soybean results, subirrigation resulted in a loss of $9.63/acre compared to drainage only. Analyzing the corn - soybean rotation, the optimum drain spacings of 66 ft for the Rains sandy loam and 98 ft for the Portsmouth soil resulted in increased net profits for subirrigation over conventional drainage of 18% for the Rains soil and 22% for the Portsmouth soil.

2.5. Directions for the Current Economic Analysis of Subirrigation

The studies summarized above provide valuable background. The issues they have raised, the approaches that were taken in the economic analyses, and the gaps they left have shaped the direction of the current study.

The Huron County and other Michigan studies of subirrigation and drainage have provided site specific information about costs, soil types, system design and management. The North Carolina studies have shown how useful simulation can be in analyzing an investment decision that has a long horizon. Simulation provides flexibility to look at water table management from several different angles and draw important conclusions about system design and the profitability of subirrigation and drainage. The two general economic studies of irrigation provided added insight into how economists approach investment analyses from a somewhat different perspective than noneconomists.

The results of all of the above studies have led to the following delineation of the decision setting in the current analysis:

The analysis is based on a hypothetical farm in Huron County in the Saginaw Bay area of Michigan. The soil at the farm is a Kilmanagh soil, the prevalent soil type in the county. The total number of cropped acres is 400, but the investment decision concerns only a 40-acre field where a drainage system is in place.

Three scenarios are hypothesized concerning water availability:

1) The farmer has access to a private surface water source.

2) The farmer has the potential to exploit ground water resources.

3) The farmer has the opportunity to participate in an irrigation district where a water use fee of between \$25 and \$35/acre must be paid.

The investment options under consideration include modifying the existing drainage only WTMS by reducing the drain spacing to 20 feet (DR20) or 30 feet (DR30), keeping the existing drainage only system intact (DR60), converting the existing drainage only WTMS into a subirrigation system at 20-ft tile spacings for a surface water source (SI20S) or a well water source (SI20W), or into a subirrigation system at 30-ft tile spacings for a surface water source (SI30S) or a well water source (SI30W), or into a subirrigation system at 60-ft tile spacings for a surface water source (SI60S) or a well water source (SI60W).

Chapter 3 provides a thorough accounting of the cost assumptions used and the approach taken in the economic analysis.

2.6. Gaps in the Study

Both the Huron County and North Carolina studies stressed that farmers use a rotation scheme and because the benefits to subirrigation-drainage vary widely by crop, a thorough economic analysis should explicitly consider the benefit of subirrigation to the rotations commonly used in subirrigated fields. Due to time limitations, the present economic analysis considers returns to corn alone. Corn was chosen because it is the largest cash crop grown in Huron County and therefore has a large economic significance for the county. In addition, of the four crops most often grown in a rotation, corn, soybeans, dry beans, and sugar beets, it is the one that has the lowest net returns per unit of output and the economic results could be interpreted as being a lower bound on what farmers could expect from investing in improving their water table management system.

A second gap is that no attempt has been made to incorporate either positive or negative environmental spillover effects in the economic analysis of subirrigation. Several studies described above in the water quality impact section and water availability section (Fogiel, 1992; Fogiel and Belcher, 1991; Kittleson et al., 1990a, 1990b; Kittleson and He,1990; He et al., 1991, 1992) have provided some insights into the environmental implications, but the present level of scientific knowledge of these effects is sufficiently limited that it is premature to incorporate environmental impacts in the present analysis. As mentioned above, current research by Michigan State University researchers at the Saginaw Rain Shelter site will eventually provide some of the necessary environmental data necessary to extend the economic analysis of subirrigation to include effects on ground and surface water contamination and erosion.

CHAPTER 3

METHODOLOGY

3.1. Introduction

Farmers are faced with many types of uncertainty in their decision environment. Production risks and financial risks are two of the most important sources of uncertainty. Production risk includes weather variability, the threat of pest infestations and disease, and uncertain consequences of production management decisions such as the choice of plant variety and cultural practices or the timing of production activities. Financial risk includes price risk and uncertainty stemming from the financial structure of the business.

Financial risk from price variability of inputs and outputs arises from forces outside the control of the farmer. On the other hand, financial risk deriving from the structure of the business is greatly affected by capital investment decisions and choice of financing arrangements for those investments, both of which are determined by the farmer.

Financial decisions which leave the farmer highly leveraged can exacerbate production and price risks because fluctuations in output or prices interfere with the farmer's ability to make regular debt payments. Yet many capital investments are in fact made to reduce production variability. Installing an irrigation system is an example of such an investment. Irrigation is characterized as a yield-increasing, risk-reducing strategy. But these advantages must be compared to large investment costs in the irrigation system and increased production costs and variable irrigation costs associated with pumping. The investment is risky from a financial perspective, so in one sense, by installing an irrigation system, the farmer might be trading production risk for financial risk (Boggess and Amerling, 1983).

This tradeoff is quite important with irrigation investment decisions in humid regions, where the variability in weather patterns over the economic life of an irrigation investment has a significant impact on the profitability of the investment (Boggess et al., 1982 and 1983; Boggess and Amerling, 1983). This dilemma arises because of the sensitivity of expected net present value (ENPV) to the sequence of net returns flowing from the investment over the lifetime of the system. If several poor rainfall years follow installation of an irrigation system, the system begins paying for itself immediately. On the other hand, if several good rainfall years follow, the system is not contributing to significantly increased returns yet is costing the farmer in principal and interest payments on the investment loan, or in the opportunity cost of lost interest if the investment was purchased with cash.

The objectives of this study are outlined in detail in the introductory chapter and the decision setting is described in Chapter 2. This chapter provides a description of the general approach used and the specific methods employed in the economic analysis of alternative water table management systems (WTMSs).

The analysis proceeds in six stages.

(1) The production and investment costs associated with growing corn under the different options are determined.

(2) The simulation model DRAINMOD is used to generate corn yield and irrigation application data for the drainage-only and subirrigation options over a 33-year period of historic weather data.

(3) Monte Carlo simulation is applied to generate one hundred 30-year NPVs by drawing randomly from the yield and irrigation volume data.

(4) The expected NPV (ENPV) and standard deviation of NPV (SDNPV) are compared across systems for both water sources.

(5) The probability distributions of NPV generated in the Monte Carlo simulation are compared in two stages:

a) using first and second degree stochastic dominance (FSD and SSD) criteria;

b) using the stochastic dominance with respect to a function efficiency criterion to compare those distributions which are not stochastically dominated by FSD or SSD.

(6) A sensitivity analysis is performed to compare the outcome of the base analysis with outcomes of analyses run with a range of product prices, investment costs, and yield assumptions.

Both the NPV analysis using the base weather sequence and the Monte Carlo simulations are performed using an investment analysis computer program written in Quick Basic by the author. The program allows great flexibility in changing parameter values of key variables for the sensitivity analysis. A copy of the QuickBasic program code is included in Appendix A.

The methods, key assumptions and relevant theoretical background for the simulation, the NPV analysis, the Monte Carlo simulation, and the risk analysis are described in detail below.

3.2. Simulation

3.2.1. Simulation as a Tool in Economic Analyses

Simulation has become an important tool for agricultural economists interested in studying decision making and risk analysis at the farm level (Anderson, 1974a). Sources of risk in agricultural production, including pests and weather, are an integral component of simulation models. In a figurative sense, the simulation models provide researchers with a computerized experimental plot (Boggess et al., 1983) where they can hold constant key decision variables in an agricultural production system and observe the results of different scenarios under a long sequence of historical weather.

For example, when considering several alternative drain spacings in a drainage or subirrigation system, the effect of a particular drain spacing under drainage only and subirrigation can be compared for the same weather sequence. Then the drain spacing can be changed and the same weather sequence run and the results compared for the different drain spacing and management regimes. This ability to make repeated comparisons of high relative precision in the same environments is unique to simulated experiments (Anderson, 1974a).

Simulation has been extremely useful in economic analyses that consider risk. Risk analysis requires information on the probability distribution of decision alternatives. Yet actual data at the farm level are rarely available for long enough time series to derive these probability distributions. Simulated yield data can fill this gap. For example, subirrigation has only been actively practiced in Michigan for just over a decade, yet hourly precipitation data is available since 1958. In this case, 33 years of yield data can be simulated for a technology that has been growing in use only in the last 10 years and for which the availability of actual yield data is very limited.

In addition, simulated yield data have an advantage over historic data in that technology is held constant in the simulation. This obviates the need to detrend the data, thus making it easier to isolate variation in output due to risk influences.

While allowing much flexibility, simulation also has certain drawbacks. As with any modeling exercise, simulation cannot possibly capture all of the complexity of an agricultural production environment. The *ceterus paribus* assumption of economics with all of its drawbacks holds for simulation as well. Most models tend to focus on one source of variability at a time. For example, weather variability over a long historic record is captured in the present analysis, but the soil is assumed to be a stable water-holding matrix of constant fertility and structure and pest and disease influences are ignored.

Some critics argue that even the variability in weather that is captured by using historic weather records in simulations still provides only a restricted sample from a stochastic process (Anderson, 1974a). In the current analysis, random draws are made from the "parent" yield distribution with the assumption that the historic weather-yield distribution provides an acceptable representation of expected future weather-yield outcomes. Given the lack of accurate weather forecasting, this approach is warranted, provided that the results are presented with the appropriate caveats about the assumptions used in the analysis.

3.2.2. DRAINMOD

The simulation model used in this analysis to study the effects of drainage and subirrigation on yields is DRAINMOD (version 4.01). It was developed by researchers at North Carolina State University at Raleigh to study and better design multicomponent water management systems comprised of surface and subsurface drainage and/or subirrigation, and/or sprinkler irrigation components. DRAINMOD uses recorded weather data to simulate the performance of a given site specific drainage design over a long period of climatological record. The model is described in detail elsewhere (Skaggs, 1981) and will be presented only briefly below.

DRAINMOD uses crop, weather, and soil input data to compute the water balance in the soil profile. It simulates infiltration and runoff processes based on the specified drainage system design and then computes daily water table depth, depth of dry zone at the surface, subsurface drainage, runoff, and evapotranspiration (ET).

The water balance results are used in the crop response component of the model. The model has three separate components that are summarized in a first-order yield equation:

$$YR = YR_w * YR_d * YR_p$$

where
YR is the relative yield,
YR_w is the relative yield under wet conditions,
YR_d is the relative yield under dry conditions,
YR_p is the relative yield if planting is late.

All three terms, YR_w, YR_d, YR_p, are expressed in percentage terms and are initially assumed to be 100%. Then subtractions from YR_w, YR_d, and YR_p are made for excessively wet conditions, excessively dry conditions, and delays in planting, respectively.

This approach assumes that there are no interactive effects among the three model components. For example, it assumes that the effect of excessive soil water conditions is independent of the existence of deficit soil water at another time in the growing season.

The relative yield output of DRAINMOD must be converted into a predicted yield in bushels per acre (bu/acre). The conversion is made by multiplying the relative yield by a maximum potential yield (POTY) figure expressed in bu/acre. For the Huron County Kilmanagh soil of this analysis, the representative maximum potential yield for nonirrigated corn is assumed to be 140 bu/acre and that for irrigated corn to be 180 bu/acre. A sensitivity analysis of the economic results to changing these POTY assumptions is performed in Chapter 4.

The input data requirements necessary to run DRAINMOD are extensive. They fall into three major categories: soil-related inputs, crop specific inputs, and drainage design inputs. Each is described briefly below and some of the most important input values used in the simulations are included in Table 3.1. A complete listing of DRAINMOD input values is included in Appendix B.

Crop specific parameters include planting date, seed bed preparation time, length of growing season, and effective rooting depth as a function of time. The actual length of time required for seedbed preparation and planting depends on size of operation, equipment and labor available, and many other factors. A period of 8 days was chosen as being typical for a Saginaw Bay area farm of 400 acres where half the acres are planted to corn and corn is the crop planted first. Values used for the other parameters are also representative of Saginaw Bay conditions.[1]

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[1] Typical values for the Saginaw Bay area were chosen after consulting with a Huron County Extension Agent, James LeCureux, and crop and soil scientists (Dr. Maurice Vitosh and Dr. Francis Pierce at Michigan State University.

TABLE 3.1: Summary of DRAINMOD Inputs

Soil Properties (Kilmanagh Soil)	
Depth to restrictive layer	125 - 150 cm
Saturated hydraulic conductivity	
x < 70 cm	3.30 cm/hr
70 cm <= x < 112 cm	2.80 cm/hr
112 cm <= x < 125 cm	< 0.15 cm/hr
Plant-available water content at wilting	0.22 cm^3/cm^3
Required drainage volume for field work	3.40 cm
Minimum daily rain to stop field work	1.27 cm
Time after rain before work can resume	2 days
Drainage System Parameters	
Drain depth	102 cm
Drain diameter	4 inches
Surface depressional storage	
poor to fair surface drainage	2.5 cm
Drain spacings	20, 30, 60 ft
Crop Parameters	
Crop	Continuous corn
Desired planting date	Not > May 10
Working time for seedbed preparation	8 days
Length of growing season	105 days
Maximum effective rooting depth	45 cm
Dry slope coefficient	1.05
Wet slope coefficient	0.68
SF	1.25
Maximum potential yield	
irrigated	180 bu/ac
nonirrigated	140 bu/ac

(Adapted from Evans et al., 1988)

Drainage system parameters are drain depth and spacing, effective depth of impermeable layer, depth of surface depressional storage, drainage coefficient, geometric parameters used in computing the drainage rate under ponded surface conditions, and depth of water in the outlet as a function of time. These values are site and system specific. A hypothetical field site was chosen and several WTMS designs elaborated by Dr. Harold Belcher in the Department of Agricultural Engineering at MSU (Appendices C and D). Values for drain depth and depth of the impermeable layer are representative of values found in Huron County. They were chosen after consulting Huron County Soil Surveys (USDA, 1980) and other publications which provide Huron County specific information (LeCureux and Booms, 1990a-d; LeCureux 1991a,b). A large surface depressional storage parameter was used to reflect poor surface drainage conditions at the hypothetical site.

Climatological inputs include hourly rainfall and daily maximum and minimum temperatures. There is no weather reporting station in Huron County that had a long enough record of hourly precipitation so data was used from the Flint National Climatological Station for the period 1958 to 1990. Flint is the closest station to the Saginaw Bay area for which hourly rainfall data are available.[2] One drawback of DRAINMOD is that it requires hourly precipitation data and these data are not readily available for many stations.

As a check of the similarity of Flint average climatological data and that for stations in Huron County, a comparison was made between average monthly temperature and precipitation data for the Flint weather station (Genesee County) and two stations in Huron County, Bad Axe and Harbor Beach (Appendix E) for the period 1951-1980. Even between the two stations in Huron County, there is quite a difference in average monthly precipitation, with Harbor Beach receiving more rainfall, especially during the growing season. Average maximum and minimum temperatures for the two Huron County sites also differ significantly. Growing season temperatures in Bad Axe are generally higher than those in Harbor Beach. Comparing the two Huron County stations with Flint, Bad Axe and Flint have very similar temperatures, while Harbor Beach and Flint have similar growing season rainfall. Flint tends to have higher average monthly rainfall than either Huron County station, except during July, when both stations have higher precipitation than Flint. Bad Axe receives 1.69 inches less rainfall than Flint

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[2] Hourly precipitation data were obtained from the Midwest Regional Climate Center, Champaign, Illinois. Daily maximum and minimum temperature data were obtained from the Michigan Department of Agriculture, Environmental Division, Department of Climatology.

during the growing season (May-September) while Harbor beach receives only 0.36 inches less than Flint over the growing season. These data are similar enough that the weather data for Flint could feasibly represent growing conditions in Huron County for the purpose of this study.

Soil property inputs for DRAINMOD include saturated hydraulic conductivity of each soil horizon, soil water characteristics, relationships for the drainage volume and steady upward flux as functions of water table depth, Green-Ampt infiltration parameters, and water content at the wilting point.

Additional soil-related inputs that allow the model to simulate trafficability constraints include threshold values for the drainage volume required for field operations during planting and harvesting periods and for the amount of rainfall necessary to postpone field operations.

Site specific soil measurements at field sites in Bannister for a Ziegenfuss soil and Bad Axe for a Kilmanagh soil were provided by Dr. James Crum of the Crop and Soil Sciences Department at Michigan State University. The saturated hydraulic conductivity values were taken from Huron County Soil Surveys (USDA, 1980). The surveys provide a range of possible values for each soil layer. For the base analysis, an average value was chosen for each layer.

All of the soil properties are very site specific, varying somewhat even within a given soil type. This necessitates site specific measurements of hydraulic conductivity, depth to restrictive layer, and soil water characteristics. This is an obvious limitation, since results of the simulations and the economic analyses derived from the yield results of the simulations must also be presented as being site specific. However, this is quite representative of reality. Each farm is unique. The present analysis provides results that farm decision makers must adapt to their own particular situation.

3.2.2.1. Model Validation

DRAINMOD has been validated using field data for North Carolina, Iowa, Ohio, and India (Skaggs et al., 1981; Hardjoamidjojo et al., 1982; Skaggs et al., 1982). Belcher validated the water balance component of DRAINMOD using field data from Bannister, Michigan, for a Ziegenfuss soil (Appendix F).

Validation of the yield component was done for the present analysis using both aggregate county-level yield data and farm-level yield data. The long-term simulations for a Kilmanagh soil and the Flint climatological station data were run using the input data shown in Table 3.1 above. Complete results of these runs are presented in Chapter 4. The results of the drainage-only simulations at a 60-ft spacing (DR60) were validated against historic Genesee County aggregate corn yield data (Michigan Department of Agriculture, 1958-91) and historic farm-level corn yield data from a farm near Reese in Tuscola County.[3] The Genesee County aggregate corn yield data were chosen over Huron County aggregate yield data because the Flint reporting station is in Genesee County. The Reese farm was chosen because of its relative proximity to the Flint weather reporting station[4] and because it has a wet loamy soil in the same soil classification category as the Kilmanagh soil of the analysis. No site-specific weather data was available for the Reese farm, so the comparability of the simulation predicted

[3] The Reese corn yield data were made available by Dr. Roy Black of the Department of Agricultural Economics at Michigan State University from TELFARM records.

[4] Reese is approximately 20 miles directly north of the Flint reporting station.

yields and the actual farm-level yields is only approximate. The same is true for the comparisons of the county-level yield data and the simulation predicted yields. The comparisons give a global view of closeness of predicted and actual yields in the study area.

In order to compare DM predicted yields with the historic yield data, it was necessary to detrend the historic yields to remove the effect of technological change. A preliminary step before detrending of the data was to test for heteroskedasticity. This was done by running a regression on corn yield versus time[5] (Figures 3.1. and 3.2.) and plotting the residuals as a function of time.

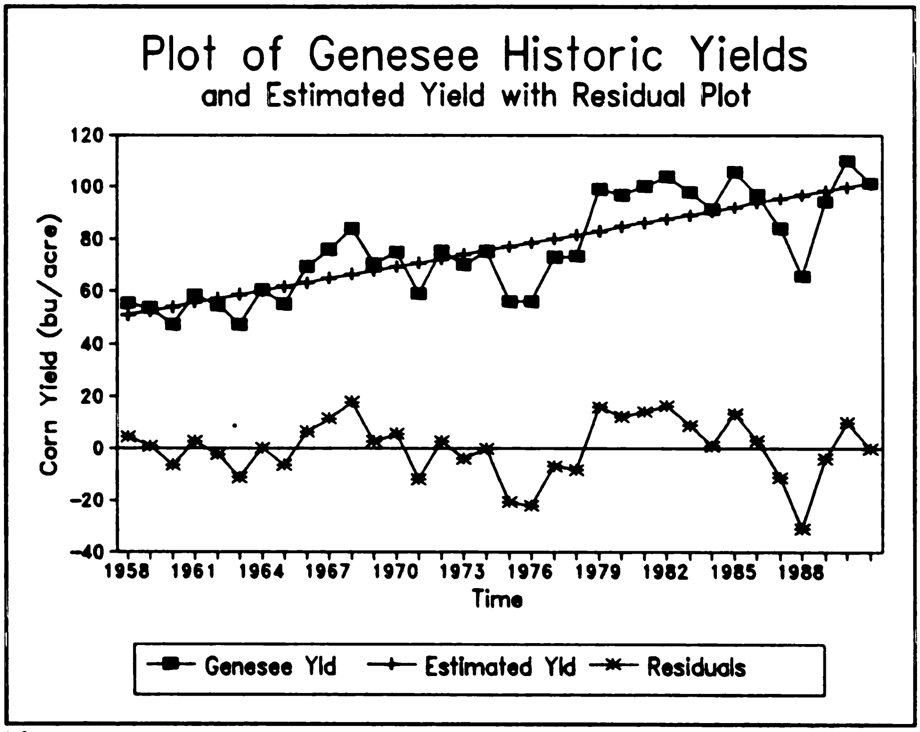


Figure 3.1.

[5] Yield data for Genesee county are for 1958 to 1991 and for the Reese farm are for 1963 to 1988.

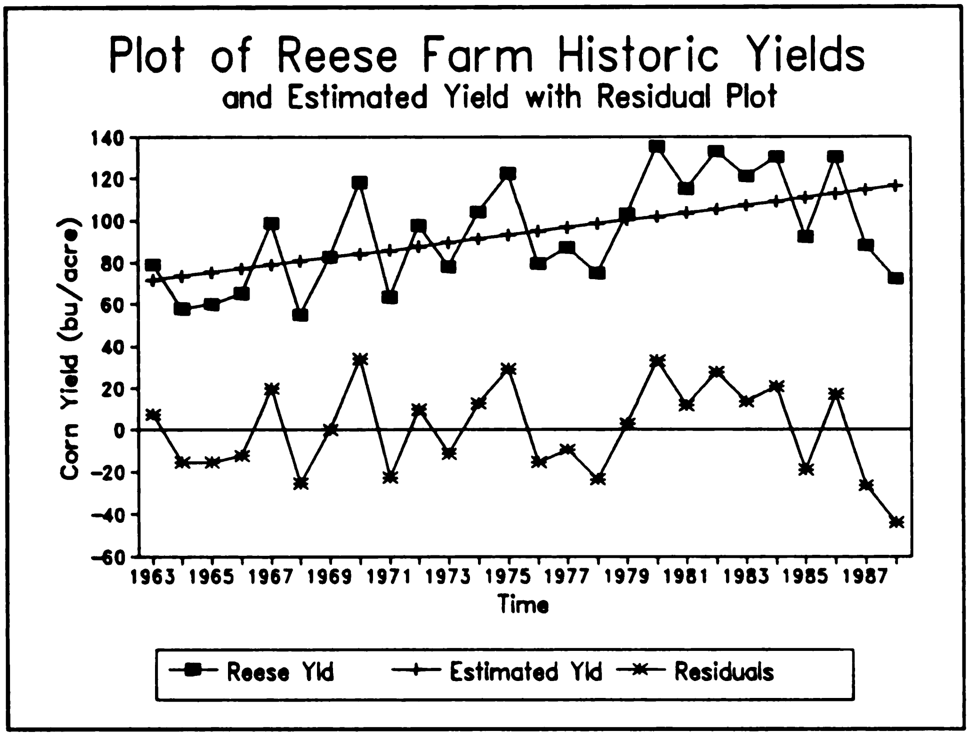


Figure 3.2.

Visual inspection of the residuals implied that heteroskedasticity was not present. However, a second check for heteroskedasticity, Spearman's rank correlation test was also preformed (Gujarati, 1978). For the Genesee historical yield data, the computed t value was 1.47 and for the Reese farm yield data it was 0.79. For both cases the t value was smaller than the critical t value (t = 2.04) at the 5% significance level, and thus we can reject the null hypothesis of heteroskedasticity.

The historic and detrended yield data along with the DRAINMOD predicted yields are presented in Tables 3.2 and 3.3. In these tables, the last column, DIF, shows the difference between the detrended historic yields and DM predicted yields (DIF = historic detrended yields minus DM predicted yields). For the Genesee County data, the average difference is -0.7 bu/acre with a standard deviation of 13.2 bu/acre. For the

Reese farm data, the average difference is -0.1 bu/ac with a standard deviation of 22.4 bu/ac. Figures 3.3. and 3.4. show graphically the detrended historic yields and the DRAINMOD predicted yields.

For the aggregate Genesee county yields, DRAINMOD accurately predicted most downward trends in yield and only once predicted a much lower yield when in fact the yield was high (1974). To some extent, in the case of low yield predictions when yields were in fact low, DRAINMOD tended to exaggerate yield losses (for example, in 1963, 1965, and 1978). For the aggregate county-level data, the standard deviation of the predicted yields was higher than for the detrended historic yields. Aggregation of yields to the county level tends to mask variability at the farm level (Fulton et al., 1988), so the higher standard deviation of the predicted yields is valid since the simulation is field specific.

For the Reese farm data, DRAINMOD performed less well. As expected, the detrended farm-level yields show much more variability. The standard deviation is 21.4 bu/acre compared with 11.4 bu/acre for the county-level data. DRAINMOD predicted yields for the 1963-1988 period had a standard deviation of 19.1 bu/acre, which was only slightly lower than that for the farm-level yields, but it missed some important downward trends in yield, missing eight of twelve significantly low historic yields. In addition, twice it predicted low yields when in fact yields were high. The weather data which the Reese farm experienced could be significantly different from those recorded at the Flint reporting station, so this comparison is a rough one. For both the county-level and farm-level yields, for example, DRAINMOD predicted very low yields for 1963 when the historic data shows average yields. However, inspection of the Flint weather for 1963 shows a period of 33 days in a critical growth stage where no significant rainfall fell.

TABLE 3.2: Genesee County Historic and Detrended Yield Compared with DM Yields

Year	Historic Yield (bu/ac)	Detrended Yield (bu/ac)	DM Predicted Yield (bu/ac)[6]	DIF
1958	55.5	105.8	110.0	-4.2
1959	53.5	102.3	90.4	-11.9
1960	47.4	94.7	94.9	-0.3
1961	58.2	103.9	107.7	-3.8
1962	54.6	98.8	110.0	-11.2
1963	47.2	89.9	61.2	28.7
1964	60.4	101.6	110.0	-8.4
1965	55.0	94.6	79.6	15.0
1966	69.4	107.5	104.8	2.7
1967	76.0	112.6	109.6	3.0
1968	83.8	118.9	110.0	8.9
1969	70.4	103.9	105.5	-1.6
1970	74.7	106.7	110.0	-3.3
1971	59.0	89.5	110.0	-20.5
1972	75.0	104.0	110.0	-6.0
1973	70.0	97.4	110.0	-12.6
1974	75.0	100.9	83.7	17.2
1975	56.0	80.4	110.0	-29.6
1976	56.1	79.0	107.8	-29.8
1977	73.1	94.4	110.0	-15.6
1978	73.3	93.1	69.4	23.7
1979	98.8	117.1	110.0	7.1
1980	96.6	113.4	110.0	3.4
1981	100.0	115.2	110.0	5.2
1982	103.8	117.5	110.0	7.5
1983	97.9	110.1	109.9	0.2
1984	91.4	102.1	99.2	2.8
1985	105.4	114.5	110.0	4.5
1986	96.7	104.3	110.0	-5.7
1987	84.0	90.1	73.9	16.2
1988	65.7	70.3	67.7	2.6
1989	94.3	97.3	110.0	-12.7
1990	109.9	111.4	110.0	1.4
1991	101.2	101.2		
Avg Dif		101.3	101.4	-0.1
SD Dif		11.4	14.9	13.2

[6] Relative Yields were converted to bu/ac yields by multiplying by a potential yield of 110 bu/ac.

TABLE 3.3: Reese Farm Historic and Detrended Yield Compared with DM Yields

Year	Historic Yield (bu/ac)	Detrended Yield (bu/ac)	DM Predicted Yield (bu/ac)[7]	DIF
1963	79.0	125.4	72.3	53.1
1964	58.0	102.6	130.0	-27.4
1965	60.0	102.8	94.1	8.7
1966	65.0	106.0	123.9	-17.9
1967	98.5	137.8	129.5	8.3
1968	55.0	92.5	130.0	-37.5
1969	82.7	118.4	124.7	-6.3
1970	118.3	152.2	130.0	22.2
1971	63.3	95.4	130.0	-34.6
1972	97.6	127.9	130.0	-2.1
1973	78.0	106.5	130.0	-23.5
1974	104.0	130.8	98.9	31.8
1975	122.2	147.2	130.0	17.2
1976	79.5	102.7	127.4	-24.7
1977	87.3	108.7	130.0	-21.3
1978	75.0	94.6	82.0	12.6
1979	103.0	120.8	130.0	-9.2
1980	135.0	151.1	130.0	21.1
1981	115.2	129.5	130.0	-0.5
1982	33.0	145.5	130.0	15.5
1983	121.0	131.7	129.9	1.8
1984	130.0	138.9	117.3	21.7
1985	92.0	99.1	130.0	30.9
1986	130.0	135.4	130.0	5.4
1987	88.0	91.6	87.4	4.2
1988	72.0	73.8	80.0	-6.2
Avg Dif		118.0	118.7	-0.7
SD Dif		21.4	19.1	22.4

Therefore, it appears that DRAINMOD accurately predicted a large yield loss under those conditions and the discrepancy possibly derives from differences in localized weather patterns. As a final check of the validity of DRAINMOD's output, the yield and irrigation application amounts for drainage only and subirrigation were shown to Dr. Jeffrey Andresen, an agrometeorologist at Michigan Department of Agriculture's Climatology Division. He judged them to be reasonable predictions after examining the daily weather data used in the simulations.

[7] Relative Yields were converted to bu/ac yields by multiplying by a potential yield of 130 bu/ac.

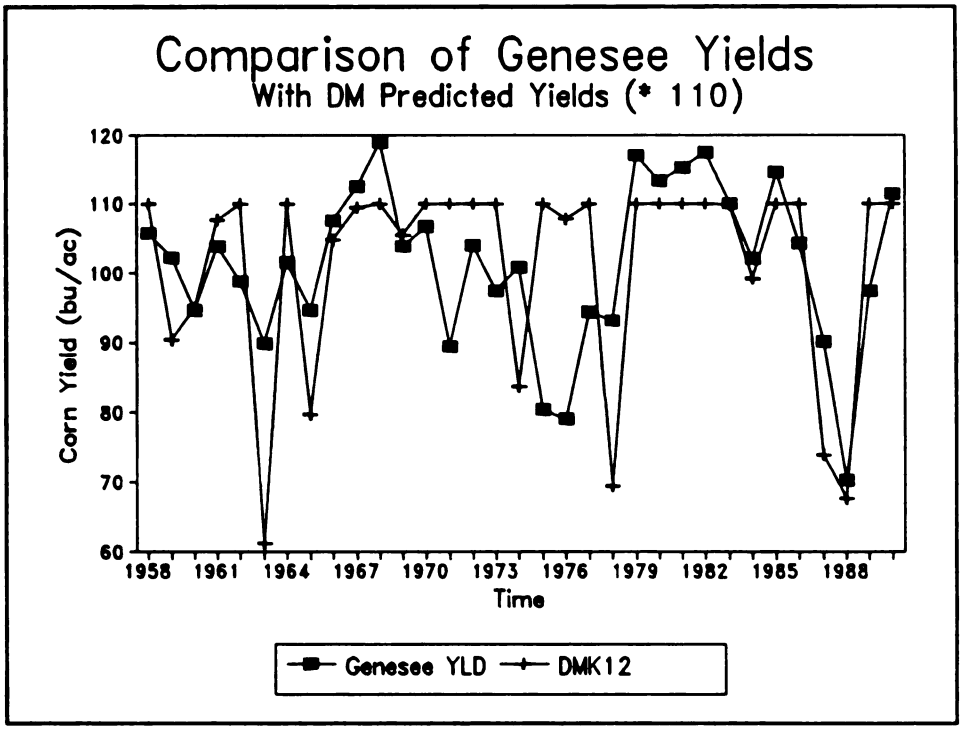


Figure 3.3.

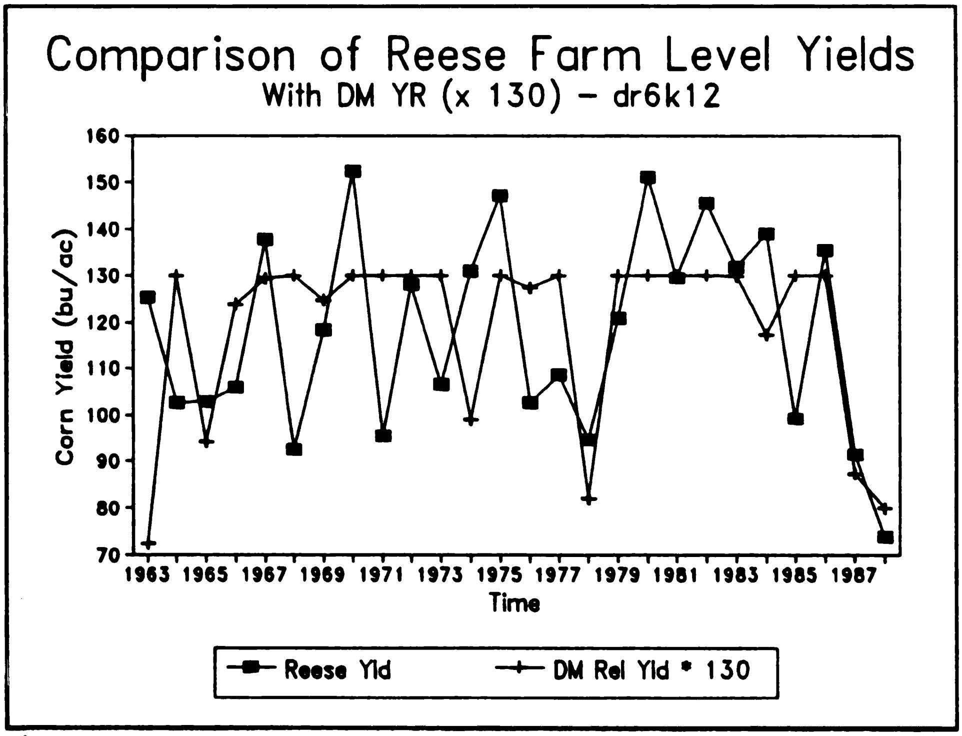


Figure 3.4.

The validation indicated that DRAINMOD provides a sufficiently reasonable approximation to the yield response to weather variability to justify using its results for the economic analysis.

3.3. Economic Analysis

In the economic analysis, base values of financial parameters are used. The values were chosen as representative of actual conditions in the Saginaw Bay area to represent a base scenario. In order to determine the sensitivity of the results of the economic analysis to changes in parameters such as marginal tax rate, price of output, the discount rate, etc. a sensitivity analysis is performed as a final component of the economic analysis.

3.3.1. Base Calculations

Annual gross income for each WTMS is calculated from DRAINMOD's predicted relative yield (YR), the assumed potential yield (POTY), and the price of corn (PC) as follows:

Annual Gross Income = YR / 100 * POTY * PC.

The potential yield is defined as the yield that would be obtained if soil water conditions were ideal during the entire growing season. The potential yield for subirrigated corn is taken to be 180 bu/acre while that for nonirrigated corn is taken to be 140 bu/acre. These figures were chosen based on historical records for the Saginaw Bay area (Michigan Department of Agriculture, 1958-1991) and after discussion with an extension agent in Huron County, James LeCureux, who is familiar with subirrigated and conventional drainage production systems.

The base corn price is held constant at $2.40/bu throughout the analysis. Since price risk is constant across management strategies in any particular year. Sensitivity analysis is carried out for alternative output prices as described in Section 3.4.

These calculations represent the annual gross income for a given water table management system, not the increase in gross income over that which would be obtained for the existing system, DR60. In Chapter 4, separate calculations of gross margins over the existing system are made in both the base weather sequence NPV analysis and in the expected value-variance analysis.

System costs include both the investment costs and variable costs associated with the operation of the system. The initial investment costs for the various WTMS options vary depending on the water supply source and the drain spacing. In this analysis, it is assumed that a conventional drainage system with 60-ft tile spacings is already in place on a 40-acre field (Appendix C). The investment options include:

DR20: Modify the existing drainage system by adding 2 extra laterals between the existing laterals so that the resulting **drainage system** has 20-ft tile spacings.

DR30: Modify the existing drainage system by adding 1 extra lateral between the existing laterals so that the resulting **drainage system** has 30-ft tile spacings.

DR60: Maintain the existing system at 60-ft tile spacings.

SI20S: Retrofit the existing drainage system to a **subirrigation system** with tile spacings at 20 feet and a surface water source for irrigation.

SI30S: Retrofit the existing drainage system to a **subirrigation system** with tile spacings at 30 feet and a surface water source for irrigation.

SI60S: Retrofit the existing drainage system to a **subirrigation system** with tile spacings at 60 feet and a surface water source for irrigation.

SI20W: Retrofit the existing drainage system to a **subirrigation system** with tile spacings at 20 feet and a well as the water source for irrigation.

SI30W: Retrofit the existing drainage system to a **subirrigation system** with tile spacings at 30 feet and a well as the water source for irrigation.

SI60W: Retrofit the existing drainage system to a **subirrigation system** with tile spacings at 60 feet and a well as the water source for irrigation.

TABLE 3.4: Description of Investment Options

Investment Option	Water Source	Description
DR20	None	Drainage only at 20-ft tile spacing
DR30	None	Drainage only at 30-ft tile spacing
DR60	None	Drainage only at 60-ft tile spacing (existing system--no investment)
SI20S	Surface	Subirrigation at 20-ft tile spacing
SI30S	Surface	Subirrigation at 30-ft tile spacing
SI60S	Surface	Subirrigation at 60-ft tile spacing
SI20W	Well	Subirrigation at 20-ft tile spacing
SI30W	Well	Subirrigation at 30-ft tile spacing
SI60W	Well	Subirrigation at 60-ft tile spacing

Site specific designs for each of nine different possible WTMSs were sent to six drainage/subirrigation contractors. Four of the six contractors provided cost estimates. In general the subirrigation/drainage contractors do not install water supply systems so estimates for the well and the pump were obtained from pump supply firms and well drilling firms.

The cost estimates provided by the drainage/subirrigation contractors for retrofitting the existing drainage system to either a drainage-only system at narrower drain spacings or a subirrigation system at three alternate drain spacings all fell within a range of $1,000. The cost estimates for the well and the pump varied significantly enough that sensitivity analysis of the economic results to these cost estimates is performed in the economic sensitivity analysis section of Chapter 4. Table 3.5 contains a summary of the average costs of individual components of the various WTMSs and Table 3.6 presents the total investment and annualized per-acre investment cost for each alternative based on a 40-acre system. Appendix G contains the complete cost estimates provided by the drainage/subirrigation contractors. For the economic analysis, the initial investment cost is broken down into per acre figures. The investment costs for the existing conventional drainage system are set to zero.

For depreciation calculations, the life expectancy of each of the different system components is as follows:

Control structure :	30 yrs
Irrigation risers :	30 yrs
Deep well :	30 yrs
Pump and electric power unit :	15 yrs
Drainage tile :	30 yrs

There are no salvage values anticipated for any of the system components.

Calculation of depreciation was done based on the straight line method. The pump is depreciated over 7 years and the other system components over 15 years. The short-term interest rate is 10.5% and the after-tax required real rate of return is assumed to be 4%.

TABLE 3.5: Summary of Component Costs for a WTMS

Component	Description and Specifications	Initial Cost
Drainage tubing	4 inch corrugated plastic pipe 6 inch diameter water supply pipe 6 inch main 8 inch main 10 inch main 12 inch main (costs include installation)	$0.37/ft $3.17/ft $1.18/ft $1.63/ft $2.66/ft $3.49/ft
Water Supply		
Deep well	8-inch, gravel-packed, 100 ft deep, 10-ft vertical lift, 200 gal/min	$15,000
SI pump & power unit	7.5 hp pump and electric motor Installation (includes intake and discharge lines) Electrical Service Hookup	$ 2,000 $ 3,000 $ 400
Surface water	River, Stream, Creek, Lake, Canal	
SI pump & power unit	3.5 horsepower pump rated at 200 gal/min Installation (includes intake and discharge lines) Electrical Service Hookup	$1,200 $3,000 $ 400
Control Structure	Head Stands Irrigation Inlets (includes installation costs)	$ 626 $ 117

Source: Sales representative and contractor estimates.

TABLE 3.6: Total Investment and Annualized Per-Acre Investment Cost for a 40-Acre System

System	Water Source	Drain Spacing (feet)	Total Investment Costs	Annualized Investment Costs (per acre)
DR20	None	20	$ 21,062	$ 30
DR30	None	30	$ 10,748	$ 16
DR60	None	60	Base Case	Base Case
SI20S	Surface	20	$ 37,740	$ 55
SI30S	Surface	30	$ 27,475	$ 40
SI60S	Surface	60	$ 17,381	$ 25
SI20W	Well	20	$ 53,540	$ 77
SI30W	Well	30	$ 43,275	$ 63
SI60W	Well	60	$ 33,181	$ 48

Water table management system operating costs can be broken down into labor costs, electricity costs, and repairs and maintenance costs for the different system components.

Conventional drainage systems do not require management. Subirrigation systems do. Different management tasks include removing flashboards from the control structure during wet periods, replacing these boards after sufficient drainage has occurred, and monitoring the water table level in the field. It is assumed that these tasks require one-quarter hour per day during the irrigation season and labor is valued at $6.00/hr for the cost calculations.

Electricity costs depend on the number of acre-inches of irrigation water applied annually and the per acre-inch cost of pumping. The per-acre annual irrigation application amounts are one of the outputs of DRAINMOD and the per-acre-inch pumping costs vary by water source. Based on Huron County studies (LeCureux and

Booms, 1990a-d; LeCureux, 1991a,b) average pumping costs were set at $2.25 per acre-inch for a well water supply and at $1.50 per acre-inch for a surface water supply. Total per-acre annual electricity costs are calculated by multiplying the acre-inch costs by the number of inches applied during the season.

The operating and repair costs for different system components were determined from relevant publications (Evans et al., 1988) and from interviews with the Huron County extension agent, Jim LeCureux. Operating costs for control structures and irrigation risers are assumed to be 1% of the average annual investment cost of each of these components. Repair and maintenance costs for pump are assumed to be 5% of average annual investment cost. All operating costs are divided by 40 acres to convert them into per acre figures.

The operating costs for each system component are summarized in Table 3.7 and the total system operating cost for each alternative WTMS is included in Table 3.8.

TABLE 3.7: Variable Costs Associated with Water Management Systems

Component	Description, specifications, and bases for cost calculations	Cost
Repairs/Maintenance		
Irrigation riser & control structure	Fixed percentage of average annual depreciation	1%/yr
Well	None assumed	
Pumps, power units	Fixed % of average annual depreciation	5%/yr
Electricity		
SI System		
Well	7.5 horsepower pump	$2.25/in
Surface source	3.5 horsepower pump	$1.50/in
Labor		
Subirrigation system	Based on 1/4 h/day from May 15 to Aug 15 to check water level in observation wells, adjust riser level, etc. at $6.00/hr, 40 acres	$3.40/ac

TABLE 3.8: System Repair and Maintenance Costs

System	Annual System Operating Costs	Annual System Operating Costs (per acre)
DR20	$ 0.00	$ 0.00
DR30	$ 0.00	$ 0.00
DR60	$ 0.00	$ 0.00
SI20S	$ 34.00	$ 0.85
SI30S	$ 34.00	$ 0.85
SI60S	$ 34.00	$ 0.85
SI20W	$ 40.00	$ 1.00
SI30W	$ 40.00	$ 1.00
SI60W	$ 40.00	$ 1.00

Enterprise budgets developed by the MSU Department of Agricultural Economics were consulted for production cost data (Nott et al., 1992) and adjusted based on Huron County specific production cost data (LeCureux and Booms 1990a-d; LeCureux, 1991a,b). The values used in the analysis are summarized in Table 3.9.

TABLE 3.9: Irrigated and Nonirrigated Corn Production Costs

Expense	SI[8]	NI[9]
Seed	29.82	26.50
Nitrogen	28.60	22.10
Phosphate	15.20	7.60
Potash	20.90	15.40
Insecticide	12.56	12.65
Equipment Repairs	18.00	18.00
Building Repairs	3.00	3.00
Total:	128.00	104.66

It should be noted that production costs do not include depreciation, insurance, rent, interest, or labor charges. Harvesting costs, which vary depending on the number of bushels harvested, are calculated separately and include costs for drying fuel, gasoline, fuel, oil, trucking, and marketing. These costs were summarized in a per bushel harvesting cost variable (PBC = $0.57) and multiplied by the number of bushels harvested each year under the various WTMSs to give variable per bushel production costs (VPBC).

[8] SI = Subirrigated Corn with 180 bu/acre yield goal.

[9] NI = Nonirrigated Corn with 140 bu/acre yield goal.

3.3.2. Net Present Value Analysis

3.3.2.1. Theory of Profit Maximization

The base net present value (NPV) analysis looks at the investment decision in risk-free terms. The base weather-yield sequence is used to derive NPV, which is a measure of the relative profitability of the different WTMS options. It is assumed that decision makers' preferences for NPV can be embodied in a utility function U(NPV) and that under the conditions of certainty depicted in this first stage of the economic analysis, the decision maker seeks to maximize utility by maximizing NPV. The decision choice facing the decision maker is simply to choose the investment with the highest NPV. In the second part of the analysis, the risk analysis, the assumption of certainty is dropped and the reality of risk is introduced. Under conditions of risk, the object is to maximize expected utility. In the results chapter, a comparison of the outcomes of the two different approaches to analyzing the investment decision is made.

3.3.2.2. Procedures

The procedure used in the NPV analysis is adapted from Boggess and Amerling (1983). Equation 3 is the formula used for NPV. Each of the variables is described below and the base values used in the analysis are summarized in Table 3.10.

$$NPV = -C_0 + \sum_{t=1}^{n} [PY_t - (IVC_t + VPC + VPBC_t) - D_t - i(IVC_t + VPC + VPBC_t)] * \frac{(1-I)}{(1+k)^t} + \sum_{t=1}^{n} \frac{D_t}{(1+k)^t} \tag{1}$$

where

C_o	=	initial investment cost,
P	=	price of corn ($2.40/bu),
Y_t	=	yield in year t,
IVC_t	=	irrigation variable cost in year t,
VPC	=	corn production cost,
$VPBC_t$	=	per bushel harvesting cost in year t,
D_t	=	tax-related depreciation charged against the irrigation system in year t,
i	=	interest rate charged on operating capital (10.5%),
I	=	investor's marginal income tax rate (28%),
k	=	investor's after-tax minimum acceptable real rate of return (4%),
n	=	life of the system in years (30).

Table 3.10: Base Parameter Values

Parameter	Base Value
P	$2.40/bu
i	$0.105
I	$0.28
k	$0.04
PBC_t	$0.57/bu
n	30 yrs

The first term of Equation 3 is the initial cash outlay. In this analysis, it is assumed that the farmer pays all of the initial investment costs out of equity. Discussions with the Huron County extension agent, James LeCureux, revealed that most farmers pay for their subirrigation systems out of harvest earnings. This assumption greatly simplifies the analysis because issues such as the farmer's leverage ratio, loan payback periods, and long-term interest rates can be set aside. However, including the discount factor in the analysis accommodates the fact that the cash outlay has an opportunity cost associated with it that is captured despite the simplifying assumption of a cash purchase of the system.

The second term is the discounted sum of after-tax income. Depreciation, which is a deductible expense, is subtracted from gross income. The term $(1\text{-}I_t)/(1+k_e)^t$ is the tax and discount adjustment factor.

Because NPV is based on after-tax cash flows rather than net income flows and depreciation is not a cash expense, the income stream must be adjusted by adding depreciation expenses back into the analysis to prevent double counting them in the cash outflows. The final term of Equation 3 reflects this adjustment (Boggess and Amerling, 1983).

All net cash flows are expressed in constant 1992 dollars. The discount rate is also a real rate of return. A real interest charge on operating capital is included in the calculations. This includes interest on variable production costs, variable irrigation costs, and variable per bushel harvesting costs.

Because different components of the WTMS have varying life expectancies, the NPV formulation in the Basic computer program is actually a variant of the above formulation. The documented source code in Appendix A provides full details of how the NPV calculations accommodated this complication.

The output of the first stage of the economic analysis is the NPV of the alternative WTMS under the base weather sequence. The base NPV results provide a risk-neutral ordering of the systems.

3.3.3. Monte Carlo Simulation

Monte Carlo simulation is used to address the importance of the sequence of weather on the profitability of water table management investments in humid climates. Monte Carlo simulation involves using random numbers in sampling from a particular distribution (Rubenstein, 1981). In this analysis, the process simulation model DRAINMOD provides a 33-year sequence of yields and irrigation application amounts derived from running the simulation for 33 years of climatological data. This 33-year sequence is an historical empirical distribution. By randomly drawing 30-year sequences with replacement from this historic distribution, we can capture the significance of the sequencing of weather on the NPV of the investment.

The sequence of Monte Carlo simulation can be depicted as follows:

1. DRAINMOD is used to generate yields (and irrigation application amounts for subirrigated treatments) for 33 years of daily historical weather data at a drain spacing of 60-ft.
2. A particular yield response (and irrigation application amount for subirrigated treatments) is selected by randomly drawing an observation from the uniform distribution of simulated results.
3. After-tax cash flow for the year is computed using the selected yield and irrigation application amount in tandem with system-specific costs.
4. Steps 2 and 3 are repeated 30 times. At the end of 30 simulated years, the net present value of the water table management investment is computed.
5. Steps 2, 3, and 4 are repeated 100 times to generate the probability distribution of the net present value of the system.
6. Steps 1-5 are repeated for each combination of drain spacing, water supply source, and water table management option.

(Modified from Boggess, et al., 1983, p. 87)

The output of the Monte Carlo simulation for the alternative water table management investment options provides us with the probability distributions that are used in the expected value variance and stochastic dominance analyses.

3.3.4. Risk Analysis

3.3.4.1. Risk Efficiency Models

Much of decision theory under uncertainty is based upon the expected utility model (EUM) which relies on expected utility maximization as its choice criterion. The utility function embodies information about the decision maker's preferences. It relates the possible outcomes of a choice to a single-valued index of desirability (King and Robison, 1984). It is thus an exact representation of preferences and therefore has much intellectual appeal. The model has limited practical application, however, because of the difficulties of estimating utility functions.

One way of getting around this problem is to use an efficiency criterion to order choices. After specifying certain restricting assumptions about a decision maker's preferences, an efficiency criterion divides the decision alternatives into an efficient set and an inefficient set. The efficient set of alternatives contains the preferred choice of any member of the class of decision makers for whom the criterion applies (King and Robison, 1981a).

The benefit of using an efficiency criterion is that by keeping the restrictions on the utility function rather general, only limited information about preferences is needed and the efficient set conforms to the utility functions of a broad class of decision makers. A disadvantage, however, is that if the restrictions are kept too general, not many choices will be eliminated as inefficient. As more restrictions are put on the utility function, this narrows the relevant class of decision makers to whom the efficient set applies and increases the discriminating power of the efficiency criteria. But more restrictions imply more knowledge of preferences. The tradeoff of generality versus discriminating power of the efficiency criteria confronts every analyst who tries to decide on the appropriate efficiency criteria. The choice in the end depends on the specific problem to be addressed and ultimately on the amount of information available about the preference function(s) of the decision maker(s).

There are several widely used risk efficiency criteria. The following four will be described below:

(1) first degree stochastic dominance;
(2) second degree stochastic dominance;
(3) expected value-variance efficiency;
(4) stochastic dominance with respect to a function, also known as generalized stochastic dominance.

Stochastic Dominance

Stochastic dominance of one distribution over another is determined by comparing cumulative distribution functions (CDF) of alternative choices. The CDFs are the integrals over the probability density functions (PDFs) of the random variable, x. For example, if the PDF is f(x) or $F_0(x)$[10], the CDF is defined as follows:

$$F_1(R) = \int_a^R f(x)\, dx \tag{2}$$

[10] Each successive integration of a PDF is denoted by higher subscripts. For example if $F_0(x) = f(x)$ denotes the PDF, $F_1(x)$ is the integral of $F_0(x)$, $F_2(x)$ is the integral of $F_1(x)$, etc.

In this formulation, it is assumed that x lies within the interval [a, b] and varies continuously over this range so that the PDFs are continuous (Anderson, 1974b). Figures 3.5. and 3.6. show graphically the PDF and the CDF.

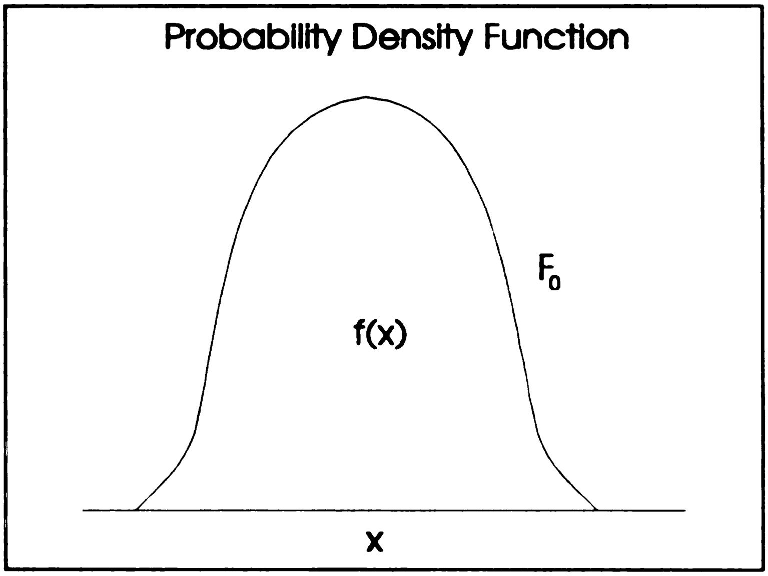


Figure 3.5.

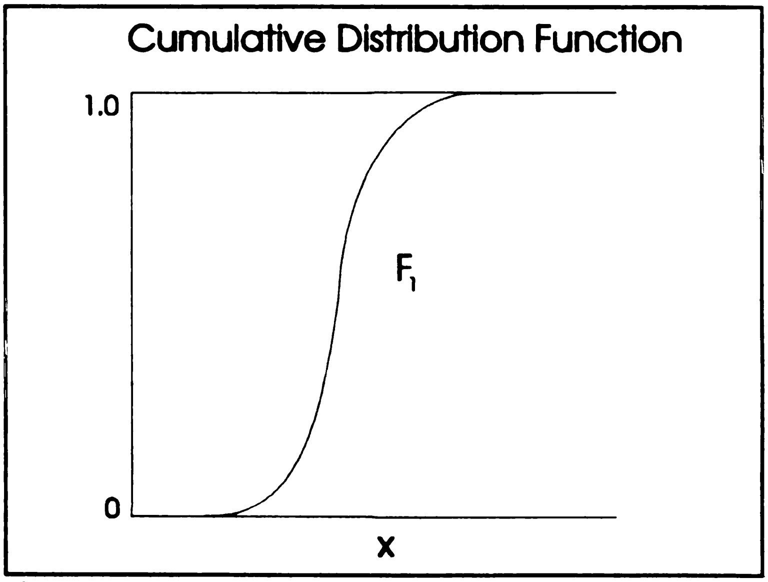


Figure 3.6.

First Degree Stochastic Dominance (FSD)

The concept of stochastic dominance rests on broad assumptions concerning the preferences of the decision maker. First degree stochastic dominance (FSD) is based on the assumption that more is preferred to less, i.e. that $U_1(x)$[11] > 0. If comparison of two CDFs shows that one is clearly less than the other, i.e., that $F_1(R) <= G_1(R)$ for all R in [a, b] with strict inequality for at least one value of R, the distribution f(x) is said to dominate g(x) by first-degree stochastic dominance. Graphically, this means that the CDF of the dominant distribution can never lie above the CDF of the dominated distribution (Figure 3.7.). FSD implies that $E(U_f) > E(U_g)$, which, in turn, means that f(x) is preferred to g(x).

Thus, without knowing anything more about the utility function other than that $U_1(x) > 0$, we can say that decision makers with such a utility function will prefer an FSD distribution (Anderson, 1974b). If one distribution does not dominate the other by FSD, the two alternatives are both considered efficient by the FSD criterion.

Following this logic, a series of pairwise comparisons is made of the various alternatives. The comparison can be made graphically, as described above, where any CDF which lies entirely above a second is considered dominated by the second. By eliminating all alternatives that are dominated, an efficient set of choices is thus determined for the finite set of alternatives under consideration (King and Robison, 1981a).

In order to further reduce the number of alternatives, second degree stochastic dominance criteria can be applied to the alternatives in the efficient set.

[11] $U_1(x)$ is the first derivative of the utility function, U(x). Higher order derivatives are shown using successively larger subscripts.

Second Degree Stochastic Dominance (SSD)

Second degree stochastic dominance (SSD) criteria are used in cases where one distribution does not clearly dominate the other by FSD, i.e., where CDFs intersect (Figure 3.7.). SSD criteria are based on the further assumption of diminishing marginal utility function -- that successive amounts of x have diminishing value to the decision maker -- $U_2(x) \leq 0$. Both assumptions taken together, $U_1(x) > 0$ and $U_2(x) \leq 0$, imply a concave utility function, U(x). Individuals with a concave utility function are said to be risk averse.

The ordering rule for SSD is that the distribution h(x) dominates g(x) by SSD if, and only if,

$$\int_{-\infty}^{R} H_1\ (R)\ dR \leq \int_{-\infty}^{R} G_1\ (R)\ dR \tag{3}$$

for all possible R in the interval with strict inequality for at least one value of R (Anderson, 1974b; Hadar and Russell, 1969). Graphically, this implies that h(x) dominates g(x) by SSD if area A is not less than area B (Figure 3.7.) or if the accumulated area under $H_1(R)$ is always less than or equal to the accumulated area under $G_1(R)$.

Application of the SSD criterion to a set of alternatives proceeds in the same manner as for FSD. Pairwise comparisons are made of alternatives. The differences between the two cumulative probability distributions are summed cumulatively in ascending order. If the cumulative sum ever changes sign, the pair cannot be ordered by SSD. If the sign never changes, the alternative with the lower bound of its CDF initially to the right of the other is the dominant alternative.

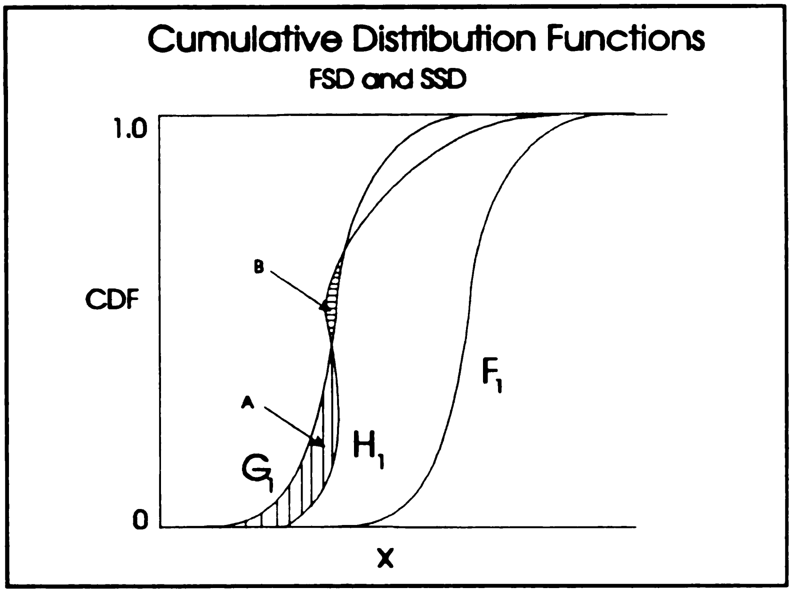


Figure 3.7.

Expected Value-Variance (EV) Efficiency

Expected value-variance (EV) efficiency is also a widely used efficiency criterion. It assumes (1) risk aversion on the part of the decision maker and either (2a) that the outcome distributions are normal, or (2b) that the decision maker has a quadratic utility function. When either 2a or 2b holds, "all relevant information concerning distributions of alternative choices is conveyed by means and variances" (King and Robison, 1984, p.73). If the distributions are normal, EV efficiency criterion is just a special case of SSD (King and Robison, 1981a).

The ordering rule for EV efficiency is as follows:

f(x) dominates g(x) if { E[f(x)] >= E[g(x)] and Var[f(x)] <= Var[g(x)] } and if at least one of the inequalities is strict.

The EV efficiency criterion has several advantages over FSD and SSD:

(i) Means and variances are easily derived.
(ii) Most analysts are familiar with the approach.
(iii) It is easily incorporated into quadratic programming.

On the other hand, the EV efficiency criterion shares some of the same disadvantages of FSD and SSD. The assumption of risk aversion means that for some decision makers who are not everywhere risk averse, a preferred choice may be eliminated from the efficient set. In addition, EV efficiency often does not effectively reduce the choice set.

EV efficiency tends to be inferior to FSD and SSD in at least one respect. The normality assumption of the EV criteria is often violated in agricultural settings. Empirical evidence indicates that agricultural yields and other measures of returns have negative skewness (Day, 1965). In Chapter 4, probability distributions of the expected NPV of the various WTMS are shown graphically and it will be seen that the distributions do show negative skewness. According to King and Robison (1984), if the normality assumption is violated, the EV efficient set can differ from the SSD efficient set. For this reason, both EV efficiency criteria and stochastic dominance criteria are applied to the economic results to determine if they identify the same efficient set.

Stochastic Dominance With Respect to a Function (SDRF)

The efficiency criteria discussed so far all suffer from two deficiencies. None will reliably reduce a large number of choices to a small efficient set that the decision maker can order directly and each relies on the assumption of risk aversion (King and Robison, 1984; Harris and Mapp, 1986). Stochastic dominance with respect to a function (SDRF) overcomes these limitations but requires more knowledge of the utility function. SDRF imposes limited restrictions on the utility function (King and Robison, 1981b; Meyer, 1977). It orders uncertain choices for decision makers whose absolute risk aversion functions are within specified lower and upper bounds of the absolute risk aversion function:

$$R_a(x) = - U_2(x) / U_1(x),$$

where U(x) is a von Neumann-Morgenstern utility function. $U_1(x)$ is assumed to be positive (more of the good is preferred to less), so a positive value of $R_a(x)$ implies a negative value of $U_2(x)$, which in turn implies a concave utility function and hence risk aversion on the part of the decision maker. A negative value of $R_a(x)$ implies risk loving on the part of the decision maker.

The solution procedure for SDRF relies on optimal control techniques. The object is to identify a utility function $U_o(x)$ which minimizes

$$\int_0^1 [G(x) - F(x)]\ U_1(x)\ dx \tag{4}$$

subject to the constraint that $R_a(x)$ lies everywhere between lower and upper bounds $r_1(x)$ and $r_2(x)$, i.e., where $r_1(x) <= R_a(x) <= r_2(x)$.

If the minimized outcome of Equation 4 is positive, the CDF F(x) is preferred to G(x) by all individuals whose risk aversion function lies within the specified bounds (King and Robison, 1981a). If it is zero, the two alternatives cannot be ordered. If it is negative, the positions of F(x) and G(x) in Equation 4 must be reversed and the equation again minimized subject to the same constraint to determine if G(x) is preferred to F(x).

This "preference interval" approach (Cochran and Raskin, 1988) requires that the class of utility functions be explicitly defined, but it still permits avoidance of the necessity of representing preferences exactly.

FSD and SSD can be related to SDRF by specifying the limits on $r_1(x)$ and $r_2(x)$ as follows:

For FSD, $r_1(x)$ = - infinity and $r_2(x)$ = + infinity

For SSD, $r_1(x)$ = 0 and $r_2(x)$ = + infinity.

3.3.4.2. Application of Stochastic Dominance Criteria to Water Table Management Investment Decisions

In this analysis, 30-year NPV from a 40-acre WTMS investment is the random variable of interest. First and second degree stochastic dominance criteria and stochastic dominance with respect to a function are used to identify the risk efficient strategies. In addition, EV analysis is also performed in order to compare the efficient set identified by the two methods.

Implementation of the SD rules involves pairwise comparison of distributions to identify and eliminate distributions that are dominated. The practicalities of this approach are discussed below.

Steps of Stochastic Analysis

1. For each distribution, rank all the values taken by x (NPV) in ascending order.
2. For each distribution, attribute $f(x_i)$ to each x_i. (For 100 NPVs, each NPV has a probability of .01 associated with it.)
3. Graph the CDF of the NPVs of each WTMS.
4. Make pairwise comparisons among distributions by applying FSD criteria to determine if one distribution dominates the other by FSD.
5. If this is not the case, apply the SSD criterion.
6. If one distribution does not dominate the other by SSD, apply the SDRF criterion.

Determination of FSD is done graphically in this analysis. Due to limitations in graphing capability, CDFs are not displayed in the traditional fashion (Figure 3.8.). Rather than having the cumulative probability on the y-axis and the expected NPV on the x-axis, the axes had to be reversed in order to display more than one CDF on each graph. Under the circumstances, dominant distributions lie above dominated distributions, i.e., f(x) dominates h(x). Any distributions that cross cannot be ordered by FSD and must be evaluated using SSD criteria, i.e., h(x) and g(x).

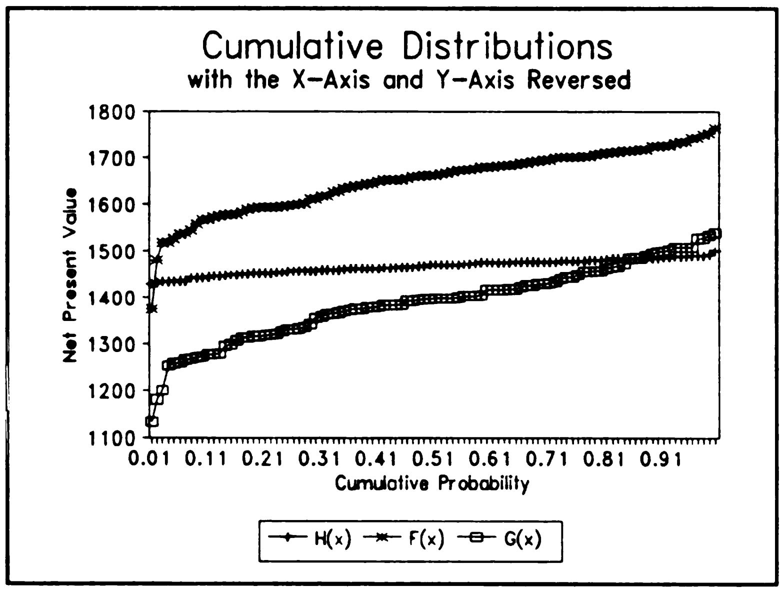


Figure 3.8.

FSD eliminates from the FSD efficient set any distributions that lie entirely below a given distribution. Determination of SSD is done by numerically integrating the cumulative difference between distributions which intersect and therefore cannot be ordered by FSD. If the cumulative sum of the difference between two such distributions does not change sign at any point, the distribution that begins above but subsequently crosses and remains below the other is said to dominate the one below it by SSD.

A computer program for ordering distributions using SDRF criteria, GSD version 3.0 (Cochran and Raskin, 1988), was used to evaluate distributions which were not dominated by either first or second degree stochastic dominance.

3.3.4.3. Application of Expected Net Present Value Criteria to Water Table Management System Investment Decisions

Expected NPV and standard deviations of NPV are compared across systems. In any case where the ENPV of one WTMS is greater than or equal to that of the other and the WTMS also has a standard deviation lower than or equal to the other, with at least one of the inequalities being strict, it is said to dominate the other by the EV criterion.

3.4. Sensitivity Analysis

The results of the economic analysis depend on the values of parameters chosen in the base scenario. In order to test the sensitivity of the results to the particular values chosen, sensitivity analyses are performed on the following parameters:

a) yield,

b) marginal tax rate,

c) product price,

d) discount rate,

e) initial cost of the WTMS.

The sensitivity analysis consists of substituting different values for each of the above parameters and determining whether the basic stochastic dominance relationships among WTMSs changes significantly. In some instances, comparisons of changes in the ENPV and SDNPV under the base scenario and the adjusted scenario are made, but the emphasis is generally on noting how changes in key parameters affect the stochastic dominance ordering of the investment options.

CHAPTER 4

RESULTS

4.1. Simulation Results

Simulations were conducted for 33 years (1958-1990) using climatological data from Flint, Michigan, for alternative drain spacings of 20, 30, and 60 feet. Both subirrigation and conventional drainage were simulated for each drain spacing and complete simulation results for each system are presented in Appendix H. Tables 4.1 and 4.2, which show the results for conventional drainage and subirrigation at 30-ft tile spacings, are presented in the text below for easy reference. Values in the Predicted Yield column are the overall relative yield multiplied by the potential yield, which is 180 bu/acre for subirrigation and 140 bu/acre for drainage only.

4.1.1. Drainage Only Results

Referring to Table 4.1 and Appendices H1-H3, the simulation results show that at the 20- and 30-ft tile spacing for drainage only, excess water stress does not result in yield reductions nor does wet stress ever result in a delay in planting at these spacings. This result is a function of the narrow drain spacing which provides excellent drainage. As the tile spacing increases to 60 feet some slight excess water stress occurs during 3 of the 33 years of the simulation. Although simulation results with tile spacings greater than 60 feet are not included in the appendix, simulations were run at 70-, 80-, 90-, and

100-ft tile spacings and excess water stress became more severe at successively wider tile spacings.

The most significant yield reductions for the drainage only scenario at 20-, 30-, and 60-ft tile spacings occur in all cases as a result of drought stress, which causes yield reductions greater than 10% in 8 of the 33 years at each tile spacing. As discussed in the previous chapter, inspection of rainfall data by an agrometeorologist at the Michigan Department of Agriculture Climatology Department, Dr. Jeffrey Andresen, confirms that the indicated years were in fact relatively dry years based on the daily weather records from the Flint reporting station.

The simulation results show a predominance of 100% yields. In fact, in just over half of the years, the predicted relative yield is 100%. Under actual field conditions, one would assume that the yields would show much more year-to-year variation. However, no correction is made for this phenomenon. The rationale for not making a correction is that under field conditions, in a good year, yields often exceed the planned yield goal (as evidenced in validation Figures 3.3 and 3.4). Yet DRAINMOD does not predict yields greater than 100% of the assumed potential yield, so to some extent the large number of 100% yields compensates for this deficiency.

In comparing the simulation results for the conventional drainage case at the three tile spacings, 20-ft, 30-ft, and 60-ft, there is a general tendency for the predicted relative yields to increase as the drain spacings increase. This occurs in all years except 1969 where, at the 60-ft drain spacing, yields fall slightly because of excess water stress. This result is significant, showing that on a Kilmanagh soil where only drainage is practiced, reducing the tile spacing below 60 feet can occasionally result in yield losses from over drainage. Later, in the economic analysis section, this fact results in the clear domination of the 60-ft tile spacing over the narrower drain spacings for the drainage only systems.

TABLE 4.1: DRAINMOD Yield Output for Drainage Only at 30-ft Tile Spacings

	Water Stress				Relative Yields				Predicted
Year	Excess	Def	Plant Date	Plant Delay	Excess	Def	Delay	Overall	Yield (bu/acre)
1958	0	0	125	0	100	100	100	100	140.0
1959	0	22.2	125	0	100	76.7	100	76.7	107.4
1960	0	14.8	125	0	100	84.5	100	84.5	118.3
1961	0	2.9	125	0	100	97.0	100	97.0	135.8
1962	0	0	125	0	100	100	100	100	140.0
1963	0	44.8	125	0	100	52.9	100	52.9	74.1
1964	0	0	125	0	100	100	100	100	140.0
1965	0	28.5	125	0	100	70.1	100	70.1	98.1
1966	0	5.7	125	0	100	94.0	100	94.0	131.6
1967	0	0.4	125	0	100	99.6	100	99.6	139.4
1968	0	0	125	0	100	100	100	100	140.0
1969	0	0	125	0	100	100	100	100	140.0
1970	0	0	125	0	100	100	100	100	140.0
1971	0	0	125	0	100	100	100	100	140.0
1972	0	0	125	0	100	100	100	100	140.0
1973	0	0	125	0	100	100	100	100	140.0
1974	2.6	23.7	125	0	98.5	75.1	100	74.0	103.6
1975	0	0	125	0	100	100	100	100	140.0
1976	0	0.4	125	0	100	99.6	100	99.6	139.4
1977	0	0	125	0	100	100	100	100	140.0
1978	0	37.6	125	0	100	60.5	100	60.5	84.7
1979	0	0	125	0	100	100	100	100	140.0
1980	0	0	125	0	100	100	100	100	140.0
1981	0	0.2	125	0	100	99.8	100	99.8	139.7
1982	0	0	125	0	100	100	100	100	140.0
1983	0	1.2	125	0	100	98.8	100	98.8	138.3
1984	0	12.3	125	0	100	87.1	100	87.1	121.9
1985	0	0	125	0	100	100	100	100	140.0
1986	0	0	125	0	100	100	100	100	140.0
1987	0	33.1	125	0	100	65.2	100	65.2	91.3
1988	0	38.2	125	0	100	59.9	100	59.9	83.9
1989	0	0	125	0	100	100	100	100	140.0
1990	0	0	125	0	100	100	100	100	140.0
Average	0	8.1	125	0	100	91.5	100	91.5	128.1

4.1.2. Subirrigation Results

Referring to Table 4.2 and Appendices H4-H6, the results for the subirrigated simulation runs show much less variability in yields. This can be expected. Irrigation is practiced to reduce yield variability. The difference between the drainage only case and the subirrigation case is that the yield losses under subirrigation at the narrower drain spacings result from excess water stress rather than drought stress. Excess water stress results under subirrigation because the water table is being held at a high level and when a rainfall event occurs under these circumstances, water invades the top 30 cm of the soil causing excess water stress and yield reductions.

DRAINMOD captures this effect very well. By varying the weir elevation in the control structure in the field, and analogously the weir setting in DRAINMOD, these yield losses due to excess water stress can be eliminated. However, a conscious decision was made to leave the weir setting in DRAINMOD at a level (55 cm) that resulted in some excess water stress because this more closely represents reality. Farmers do not have total control of the water table depth on a continual basis. Having an optimal weir level setting in DRAINMOD would imply superior management which is not the case in field situations.

Consequently, the simulation results show wet stress under subirrigation diminishing as the drain spacing increases. Conversely, at the 60-ft spacing, drought stress begins to cause yield reductions. This reflects actual experience in Huron County. At a wider drain spacing, water does not move laterally through the soil far enough to reach the middle portion of the field between two tiles. Inspection of the irrigation volumes (Appendices I1-I6) shows that in moving from 20- to 30- to 60-ft tile spacings, successively smaller volumes of water can be pumped out through the tiles. At the 60-ft tile spacing water becomes limiting enough that drought stresses result.

A graph of the predicted yields converted into bushels per acre is presented in Figure 4.1 for the drainage only system and the subirrigation system at 30-ft tile spacings. This graph clearly shows that because of the difference in the assumed potential maximum yields between the two systems (180 bu/acre for subirrigation versus 140 bu/acre for drainage only), the subirrigated system consistently has higher yields than the drainage only system. The sensitivity of the economic analysis to these differences in assumed potential yields is tested below in the economic sensitivity analysis section.

TABLE 4.2: DRAINMOD Yield Output for Subirrigation at 30-ft Tile Spacings

Year	Water Stress Excess	Water Stress Def	Plant Date	Plant Delay	Relative Yields Excess	Relative Yields Def	Relative Yields Delay	Relative Yields Overall	Predicted Yield (bu/acre)
1958	0	0	125	0	100	100	100	100	180.0
1959	5.9	0	125	0	96.0	100	100	96.0	172.8
1960	0	0	125	0	100	100	100	100	180.0
1961	0	0	125	0	100	100	100	100	179.5
1962	0.5	0	125	0	99.7	100	100	99.7	180.0
1963	0	0	125	0	100	100	100	100	180.0
1964	0	0	125	0	100	100	100	100	180.0
1965	0	0	125	0	100	100	100	100	180.0
1966	0	0	125	0	100	100	100	100	180.0
1967	1.7	0.1	125	0	98.8	99.9	100	98.8	177.8
1968	11.9	0	125	0	91.9	100	100	91.9	165.4
1969	8.3	0	125	0	94.3	100	100	94.3	169.7
1970	7.3	0	125	0	95.0	100	100	95.0	171.0
1971	0	0	125	0	100	100	100	100	180.0
1972	10.2	0	125	0	93.1	100	100	93.1	167.6
1973	0	0	125	0	100	100	100	100	180.0
1974	4.9	0	125	0	96.7	100	100	96.7	174.1
1975	0.2	0	125	0	99.9	100	100	99.9	179.8
1976	2.6	0	125	0	98.2	100	100	98.2	176.8
1977	0	0	125	0	100	100	100	100	180.0
1978	0	0	125	0	100	100	100	100	180.0
1979	0.7	0	125	0	99.5	100	100	99.5	179.1
1980	3.4	0	125	0	97.7	100	100	97.7	175.9
1981	0	0	125	0	100	100	100	100	180.0
1982	0	0	125	0	100	100	100	100	180.0
1983	0.7	0	125	0	99.6	100	100	99.6	179.3
1984	0	0	125	0	100	100	100	100	180.0
1985	0	0	125	0	100	100	100	100	180.0
1986	0	0	125	0	100	100	100	100	180.0
1987	0	0	125	0	100	100	100	100	180.0
1988	0	0	125	0	100	100	100	100	180.0
1989	0.4	0	125	0	99.7	100	100	99.7	179.5
1990	0	0	125	0	100	100	100	100	180.0
Average	1.8	0	125	0	98.8	100	100	98.8	177.8

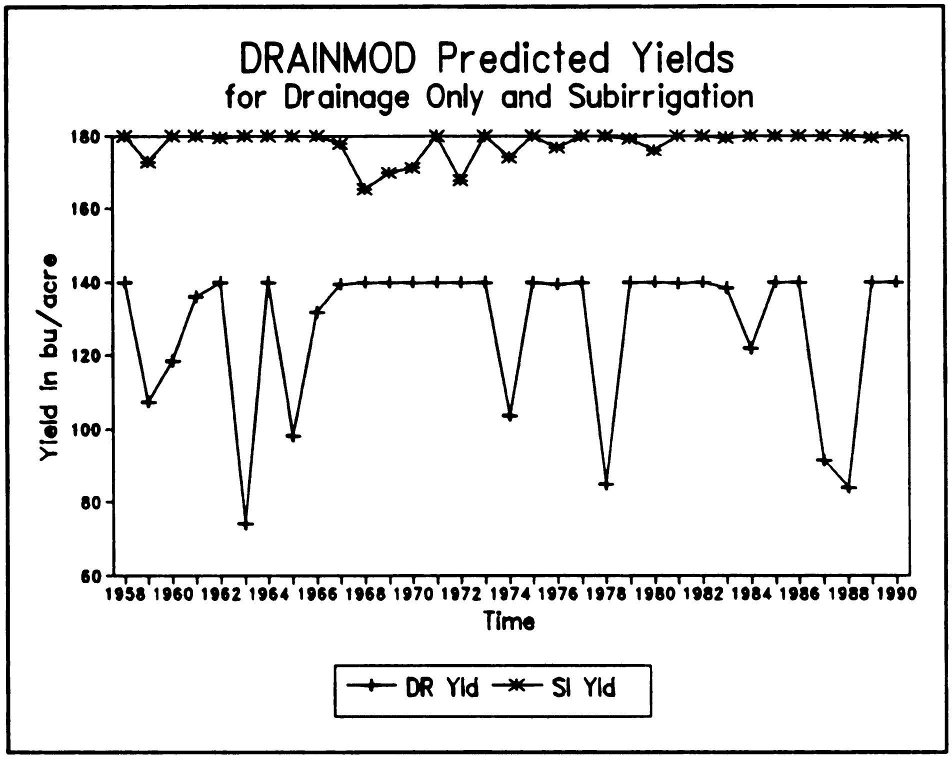


Figure 4.1

4.2. Results of the Economic Analysis

The economic analysis proceeded in three stages: an analysis of NPV using the base weather sequence, an analysis of expected NPV, and a risk analysis using the probability distribution of NPVs which were derived using Monte Carlo simulation techniques. The results of all three stages are discussed below.

4.2.1. NPV Analysis - Base Weather Sequence

As described in the methodology chapter, the NPV for each WTMS was calculated using the following formulation of the NPV equation.

$$NPV = -C_0 + \sum_{t=1}^{n}[PY_t - (IVC_t + VPC + VPBC_t) - D_t - i(IVC_t + VPC + VPBC_t)] * \frac{(1-T)}{(1+k)^t} + \sum_{t=1}^{n}\frac{D_t}{(1+k)^t}$$

The results of the economic analysis of NPV under the base weather sequence (1958-1987) over the 30-yr planning horizon are shown in Table 4.3, which includes a "Gross Margins" column showing the difference in the NPV of the various WTMS over the existing system, DR60. In addition, Table 4.4 shows the cumulative NPV over the entire 30-year planning horizon for each system. These yearly figures show how the final NPV figure is derived. They were printed out after each loop of the NPV calculation.

TABLE 4.3: NPV and Gross Margins - Base Weather Sequence (1958-87)

Investment Option	Net Present Value	Annualized Net Present Value	Gross Margin Over DR60	Annualized Gross Margins
DR20	$ 954	$ 55	-$ 446	-$ 26
DR30	$1,164	$ 67	-$ 236	-$ 14
DR60	$1,400	$ 81	------	-------
SI20S	$1,341	$ 76	-$ 59	-$ 3
SI30S	$1,598	$ 92	$ 198	$ 11
SI60S	$1,761	$ 102	$ 367	$ 21
SI20W	$1,019	$ 59	-$ 381	-$ 22
SI30W	$1,276	$ 74	-$ 124	-$ 7
SI60W	$1,444	$ 84	$ 44	$ 3

A basic interpretation of the NPV figures can be stated as follows: Under the base weather sequence, a farmer who has an existing drainage system in place and who is growing continuous corn can expect the present value of his/her net income stream over a 30-year planning horizon to be $1,400 per acre. Dividing $1,400 by the value

17.292 from a Present Value of Annuity Table (Harsh et al., 1981) for 4% real interest and a 30-year planning horizon, this figure can be annualized and interpreted as meaning the farmer would be indifferent between receiving $81 in annual per acre net returns over the 30-year period and receiving $1,400/acre today.

In comparing the $1,400 figure to the NPV for the other WTMS options, it is clear that WTMS options DR20, DR30, SI20S, SI20W, and SI30W are not profitable while WTMS options SI30S, SI60S, and SI60W offer the farmer an opportunity to earn more per acre than he/she can expect to earn with the existing WTMS. These results indicate that under a no risk situation, if the farmer chooses only to maximize NPV, only three of the six subirrigation WTMS options are more profitable than the existing drainage only WTMS.

Annualized gross margins, which are also included in Table 4.3, give a global view of what the level of annual returns over the returns from the existing system might look like. SI60S has the largest annualized gross margin of $21/acre. This figure could be used as a basis to determine a willingness to pay measure if an irrigation district were to be formed. However the $21/acre figure would have to be considered an upper bound of what farmers would be willing to pay since in the calculation of production costs for all WTMSs, labor costs and fixed costs such as insurance, land rent, and any depreciation and interest costs not associated with the WTMS investment itself were not included.

The cumulative NPV figures in Table 4.4 give a better idea of the "payoff period" of each investment alternative under the base weather sequence. Negative figures in Table 4.4 indicate that the initial cost of the investment has not yet been recuperated. Generally, in a gross margins type analysis where results are reported in terms of gross margins over the existing system, the payback period would be considered the period where the NPV stream is negative and then just becomes positive. In this analysis, although results in Table 4.4 are not reported in terms of gross margins over the existing system, the point at which the NPV stream becomes positive is still referred to as the payback period. A separate distinction is made between the payback period, as used in this context, and the point where the investment under consideration yields a NPV that surpasses that of the existing system during the investment planning horizon.

TABLE 4.4: NPV of WTMS Options over the Planning Horizon (1958-87)

YEAR	DR20	DR30	DR60	SI20S	SI30S	SI60S	SI20W	SI30W	SI60W
1958	-426	-173	91	-802	-550	-303	-1190	-938	-690
1959	-369	-119	150	-680	-427	-175	-1060	-808	-556
1960	-302	-55	212	-549	-301	-53	-922	-675	-427
1961	-217	26	290	-423	-180	65	-790	-547	-302
1962	-131	108	368	-302	-63	177	-663	-424	-184
1963	-115	121	381	-186	49	261	-541	-306	-94
1964	-35	197	453	-76	157	365	-425	-192	16
1965	2	231	486	29	257	457	-315	-86	114
1966	67	294	547	129	354	546	-210	15	207
1967	138	361	610	222	445	635	-112	111	301
1968	206	425	672	288	522	718	-42	192	388
1969	271	488	727	366	600	795	40	274	469
1970	334	548	784	444	676	875	123	354	553
1971	394	606	839	526	755	952	209	438	634
1972	452	661	891	595	823	1025	281	509	712
1973	503	712	942	649	877	1080	325	553	756
1974	528	737	969	715	941	1136	392	617	812
1975	575	783	1016	777	1005	1200	454	682	877
1976	619	828	1059	824	1066	1261	501	743	938
1977	663	872	1102	884	1126	1321	561	803	998
1978	673	882	1115	942	1184	1373	619	861	1051
1979	713	922	1155	989	1239	1429	667	916	1106
1980	752	961	1193	1034	1290	1480	711	968	1158
1981	788	998	1231	1083	1339	1530	761	1017	1207
1982	824	1033	1266	1131	1387	1577	808	1065	1255
1983	857	1067	1300	1175	1432	1623	853	1110	1301
1984	882	1092	1327	1219	1476	1667	897	1154	1345
1985	914	1123	1359	1261	1519	1709	939	1196	1387
1986	944	1154	1389	1302	1559	1750	979	1237	1428
1987	954	1164	1400	1341	1598	1767	1019	1276	1444
NPV:	954	1064	1400	1341	1598	1767	1019	1276	1444

The cumulative NPV results for each group of investments, DR20, DR30, and DR60 (Drainage Only), SI20S, SI30S, and SI60S (Subirrigation with a Surface Water Source) and SI20W, SI30W, and SI60W (Subirrigation with a Well Water Source), are discussed separately below. In each case, the existing WTMS (DR60) is also compared to the subirrigation options in each group to give a better idea of how the existing system compares with the subirrigation WTMS options for each water source. The cumulative NPVs for each group of WTMS are presented graphically in Figures 4.2 - 4.4. Figures 4.3 and 4.4 show DR60 compared with the subirrigation WTMSs in each group.

Of the drainage only WTMS (Figure 4.2), the unmodified existing system (DR60) provides the highest NPV. Because no initial investment is made, returns are positive over the entire planning horizon, whereas for DR20 and DR30, returns do not become positive until years 8 (1965) and 4 (1961), respectively.

The simulation yield results already gave us a premonition of this outcome. Improving drainage by decreasing the drain spacing below the existing 60-ft spacing for a Kilmanagh soil is not an economically viable decision for farmers. Because of the clear dominance of DR60 over the other two drainage only WTMSs, in the subsequent comparisons with subirrigation WTMSs, DR60 is the only drainage only option considered.

For the surface water subirrigation options, SI60S has the highest NPV of the three (Figure 4.3). Returns become positive in year four of this investment and the NPV over the 30-yr planning horizon is $1,767. The payback periods for the other two surface water subirrigation WTMSs are 8 years for SI20s and 6 years for SI30S.

The fact that SI60S is economically more profitable than SI30S is noteworthy. The yield results for the two systems indicated that SI30S outperformed SI60S because at the 60-ft tile spacing, water could not be pumped adequately to the center of the field between two tiles. The economic results indicate, however, that the yield benefit of the narrower tile spacing does not compensate for the extra cost of reducing the tile spacing to 30 feet.

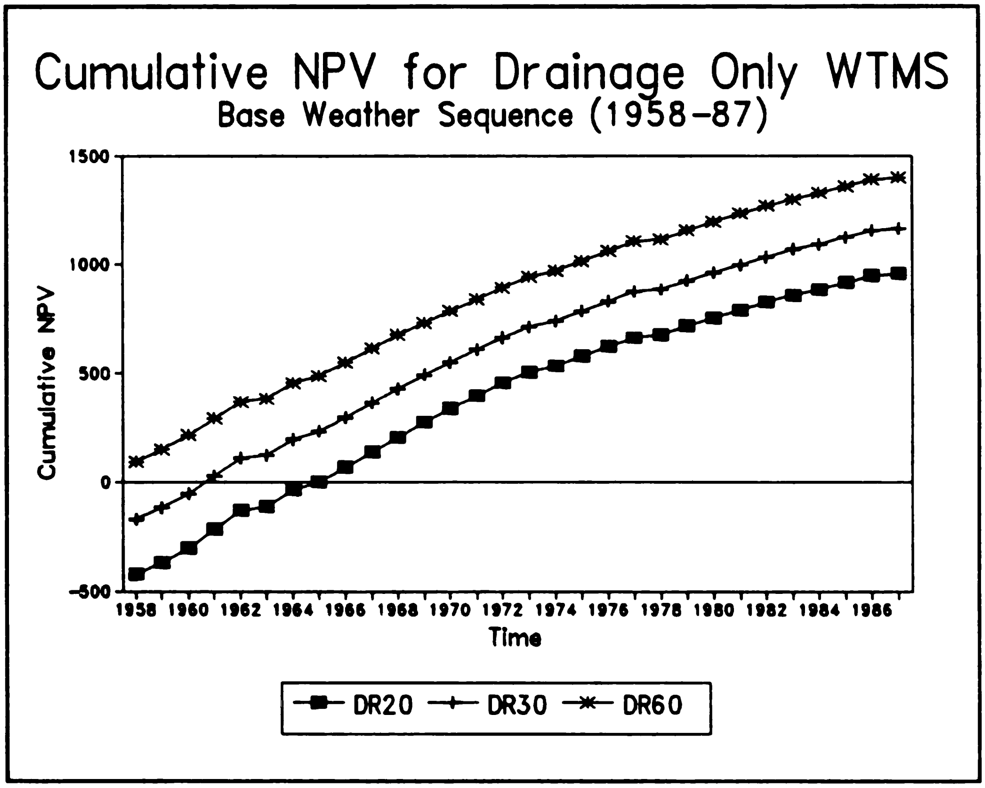


Figure 4.2

In comparing DR60, the existing system, with the the three surface water subirrigation systems, it is already clear just from looking at the NPVs for these systems that DR60 is more profitable than SI20S and less profitable than SI30S and SI60S. What is interesting to note, however, is how long into the planning horizon DR60 remains dominant over SI30S and SI60S. The NPV of SI60S does not overtake that of DR60 until year 10 of the planning horizon (1967) and the NPV of SI30S overtakes that of DR60 in year 20 (1977).

The extra information provided by comparing NPV streams of the different investment options over the planning horizon is a matter of interest to decision makers. For example, even given the fact that SI30S eventually provides a higher NPV than DR60, many farmers would not be willing to wait 20 years for the extra benefit from their investment to kick in.

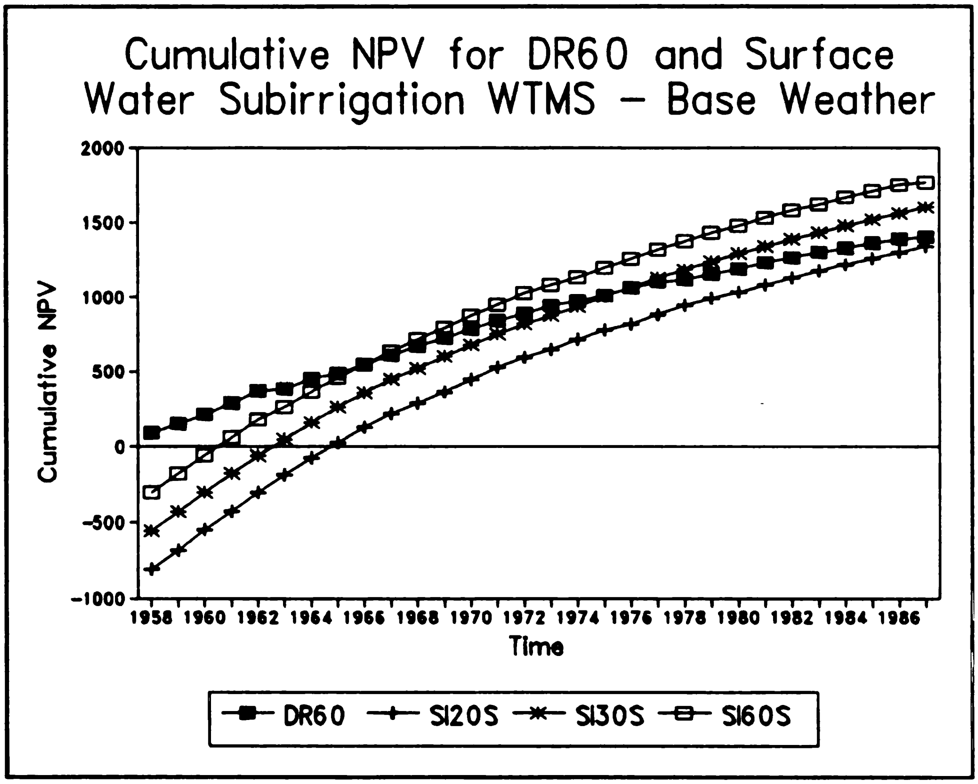


Figure 4.3

The economic results for the WTMS under subirrigation with a well water source (shown in Figure 4.4) mimic those for a surface water source except that the NPV stream does not become positive until later and is lower in each case over the 30-year planning horizon because of the higher initial investment cost associated with installing a well. In this case, DR60 has a higher final NPV than either SI20W or SI30W, and although SI60W has a higher final NPV than DR60, it only overtakes it in year 27 of the planning horizon.

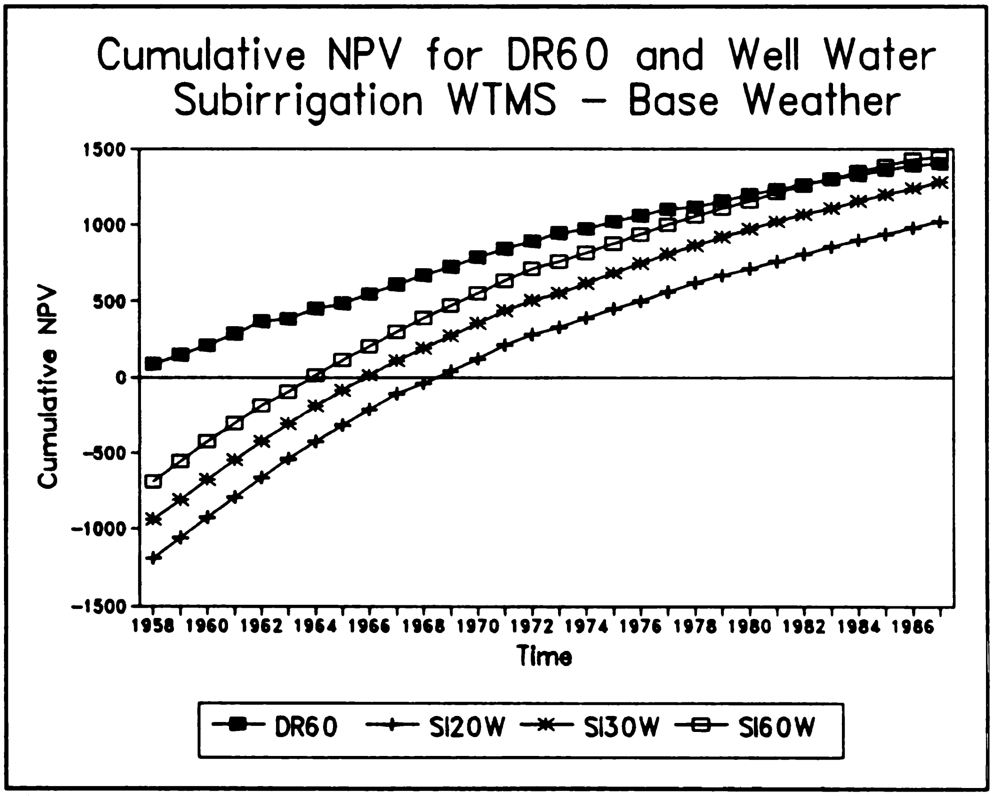


Figure 4.4

These results occurred because of the particular sequence of weather following the initial investment. Had more bad weather years followed installation of the subirrigation systems, the systems would have had a positive NPV stream sooner and would have dominated the existing system earlier in the planning horizon. This point brings us neatly to the next stage of the analysis.

4.2.2. Net Present Value and Expected Value-Variance Analysis

Use of Monte Carlo simulation techniques to generate distributions of 100 NPVs from the alternative investments captures the implications of weather sequence on the profitability of an irrigation investment. Expected NPV (ENPV) and standard deviation of NPV (SDNPV) are calculated from the NPV distributions. These results are presented in Table 4.5. Also included in Table 4.5 is a Gross Margins column which shows the difference between the ENPV of each WTMS option and DR60, the existing system. These results are evaluated from two perspectives. First, it is instructive to look at the ENPV results as if risk were not an issue, i.e., ignoring the standard deviations, and compare them with the NPV results from above. Second, risk can be addressed by applying EV efficiency criteria.

Comparing the various options, we see in the Gross Margins column of Table 4.5 that if we ignore differences in standard deviation, DR60 has a higher ENPV than any option except SI30S and SI60S, and therefore would be the preferred choice compared to the options with lower ENPV under a situation of profit maximization under certainty. These are the conditions considered above in the NPV analysis for the base weather sequence. However, the results here are surprisingly different.

TABLE 4.5: Expected NPV, SD of NPV, and Gross Margins Over DR60

SYSTEM	ENPV	SDNPV	GROSS MARGIN[1]	Annualized Gross Margin
DR20	$ 947	$ 88	-$442	-$ 26
DR20	$1,156	$ 88	-$233	-$ 14
DR60	$1,389	$ 82	-----	------
SI20S	$1,187	$ 31	-$202	-$ 12
SI30S	$1,466	$ 16	$ 77	$ 4
SI60S	$1,650	$ 68	$261	$ 19
SI20W	$ 782	$ 30	-$607	-$ 35
SI30W	$1,073	$ 16	-$316	-$ 18
SI60W	$1,292	$ 67	-$ 97	-$ 6

Table 4.6 reproduces the NPV and ENPV results for easy reference. In general, the results are similar, as should be expected. However, comparing the two results, the subirrigation alternatives fared much better under the base weather sequence than under the Monte Carlo distribution of weather-yield outcomes. The DIF column shows the difference between the the two results, with DIF = NPV - ENPV. Under the base weather sequence, the NPV is in each case over $100 greater than the ENPV for the subirrigation options. This shows that the particular sequence of weather following installation of the subirrigation system under the base sequence of weather turned out to be a "lucky draw" for subirrigation options. If this had been the only approach taken, conclusions might have been biased in favor of the subirrigation options. Including the Monte Carlo simulation, which essentially consists of randomly drawing one hundred 30-year sequences of weather-yield outcomes to generate a probability distribution of NPVs,

[1] Gross Margin refers to the difference between the ENPV of the existing system, DR60, and the ENPV of the investment alternative.

allows us to handle the randomness of weather. Comparing the NPV results under the base weather sequence with the ENPV results gives a much better appreciation of the sensitivity of NPV results to a particular "draw" of weather.

TABLE 4.6: Comparison of NPV and ENPV

SYSTEM	NPV	ENPV	DIF[2]
DR20	$ 954	$ 947	$ 7
DR20	$1,164	$1,156	$ 8
DR60	$1,400	$1,389	$ 11
SI20S	$1,341	$1,187	$154
SI30S	$1,598	$1,466	$132
SI60S	$1,767	$1,650	$117
SI20W	$1,019	$ 782	$237
SI30W	$1,276	$1,073	$203
SI60W	$1,444	$1,292	$152

Up to this point, risk has not been taken into consideration. The benefit of subirrigation that is not captured by looking at either NPV or ENPV alone is its contribution to reducing variability of returns. Inspection of the standard deviations in Table 4.5 shows that in all cases, the subirrigation options have lower variability of returns than the drainage only options. Application of EV efficiency criteria to the drainage only options reveals that the DR60 dominates the other options because it has both higher ENPV and lower SDNPV than DR20 and DR30. DR60 must be compared separately with the surface water subirrigation options and the well water subirrigation options to reflect the two mutually exclusive water source situations available in the decision environment of this analysis. In comparing DR60 with the surface water

[2] DIF is the difference between NPV and ENPV, i.e., NPV - ENPV.

subirrigation options, it is dominated by SI30S and SI60S. Comparison of DR60 with the well water subirrigation options reveals that the existing system remains in the efficient set with all the three alternative options.

Using EV efficiency criteria alone, the choice set between SI30S and SI60S and between DR60 and the well water subirrigation options cannot be further reduced to one efficient option for each set because the choice depends on the risk preferences of the decision maker. For example, while SI60S has a higher expected NPV it also shows more dispersion about that value as measured by a higher standard deviation. SI30S has a lower ENPV, but it also has a lower standard deviation and might be preferred by some decision makers who desire more stable returns, even if that means accepting a lower expected NPV.

Graphically, the variability and level of returns can be easily visualized for the different WTMS options. The probability distribution of NPV for DR60, SI60W, SI30S, and SI60S is depicted in Figures 4.5 - 4.8. This graphical presentation gives us a better appreciation of the tradeoff between variability versus level of ENPV. Comparing SI30S and SI60S, we can clearly see that the probability of getting a higher return with SI60S is quite high, but we can see equally well that a farmer who does not want to risk the slight probability of the lower returns in the negative tail of the distribution might feasibly choose SI30S, where all the probability is essentially concentrated over the $1400 NPV interval.

Some of the distributions of NPV are somewhat negatively skewed. This raises the issue of whether the EV criteria should be used to order distributions because the normality assumption is violated. Below stochastic dominance criteria are applied to the different options to see if the same efficient set is identified.

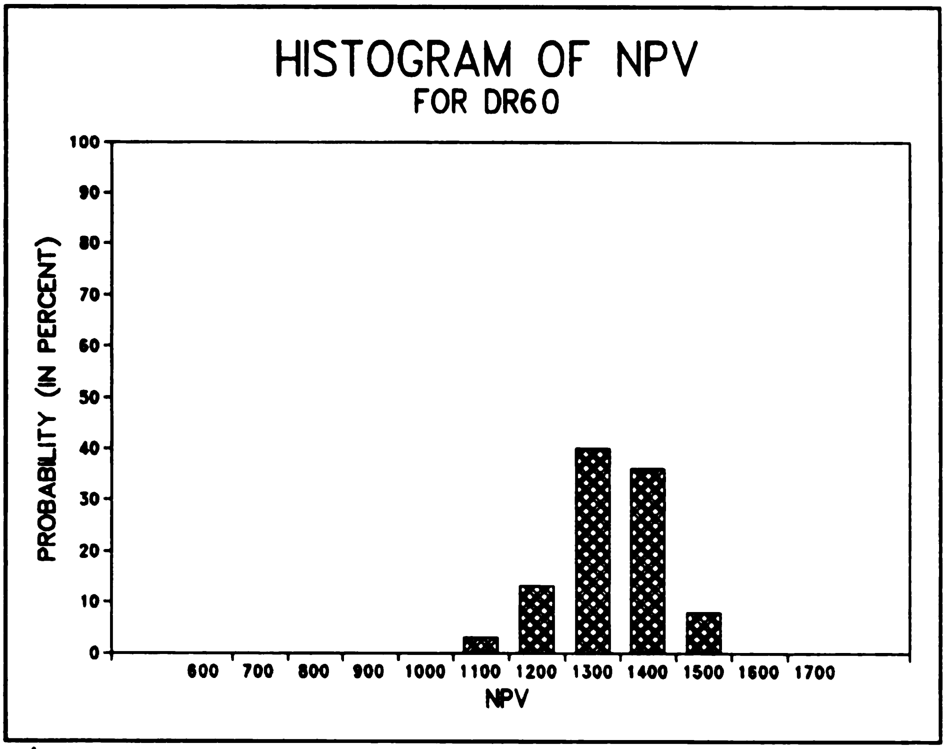


Figure 4.5.

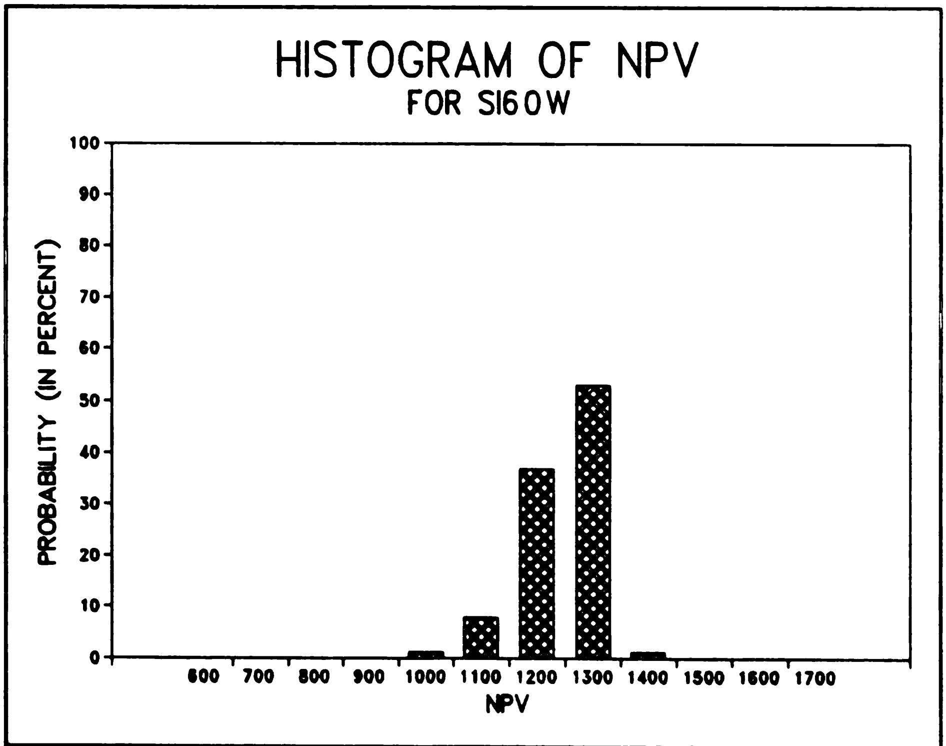


Figure 4.6.

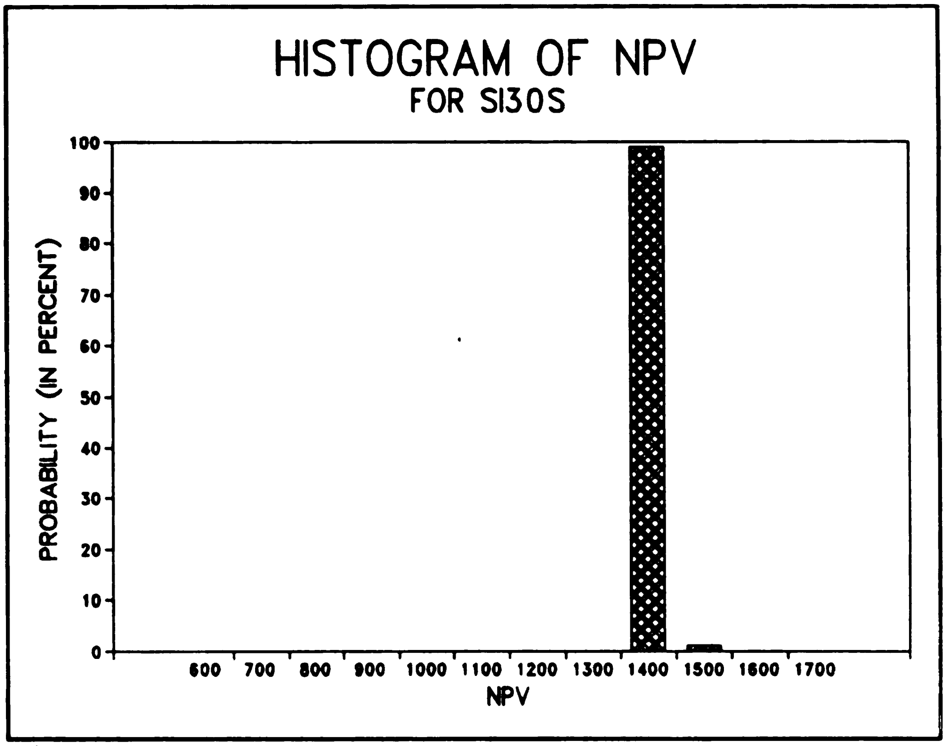


Figure 4.7.

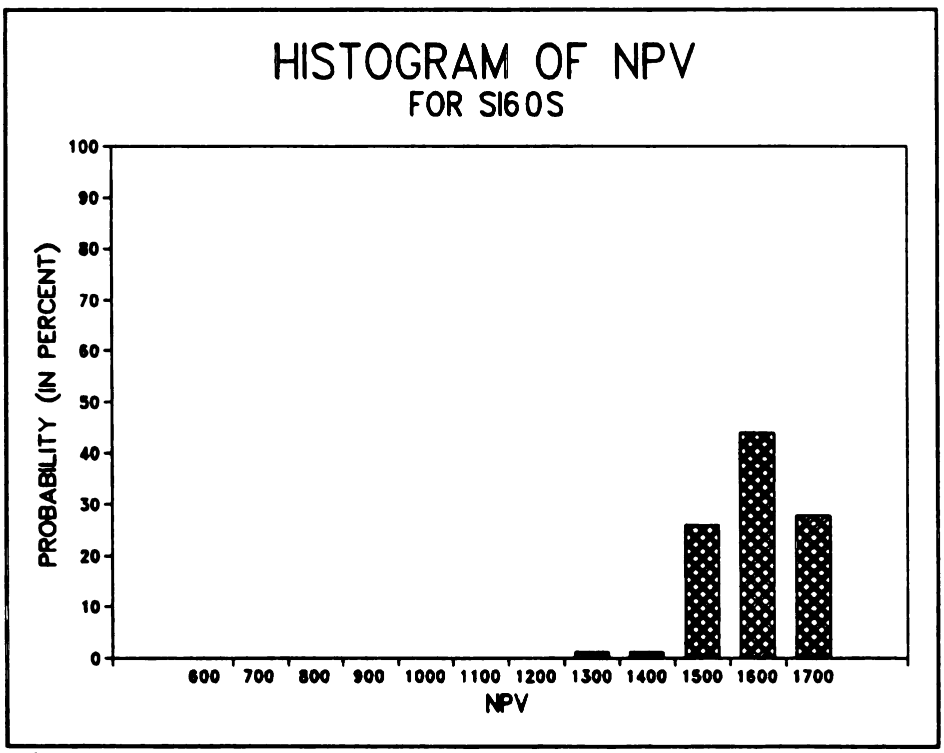


Figure 4.8.

4.2.3. Stochastic Dominance Analysis

Using a graphical approach as described in the methodology chapter, application of FSD criteria allows us to eliminate inefficient distributions. First, DR60 is compared to the other drainage only options and then to the surface and well water source subirrigation options. For the drainage only WTMSs, DR60 dominates the other two by FSD (Figure 4.9). For surface water source subirrigation systems, SI20S is dominated by SI30S, SI60S, and DR60 by FSD (Figure 4.10). SI60S dominates DR60 by FSD. The ordering of DR60 and SI30S and the ordering of SI60S and SI30S must be determined by applying SSD criteria. For the well water source subirrigation systems, DR60 dominates all three options by FSD (Figure 4.11).

In applying SSD criteria, the cumulative difference between the sets of CDFs (DR60 and SI30S; SI60S and SI30S) are evaluated to determine whether the cumulative sum of their differences ever changes sign. In the case of the SI30S - SI60S pair, a sign change does occur, meaning that the two options cannot be ordered by SSD criteria. For the DR60 - SI30S pair, no sign change occurs, so SI30S dominates DR60 by SSD.

At this point we are left with a narrower choice set than the EV approach indicated: SI30S and SI60S still cannot be ordered, but the choice between DR60 and SI30S has been narrowed to SI30S by application of SSD criteria.

As a final step in the risk analysis, the SI60S - SI30S pair is subjected to SDRF criteria.

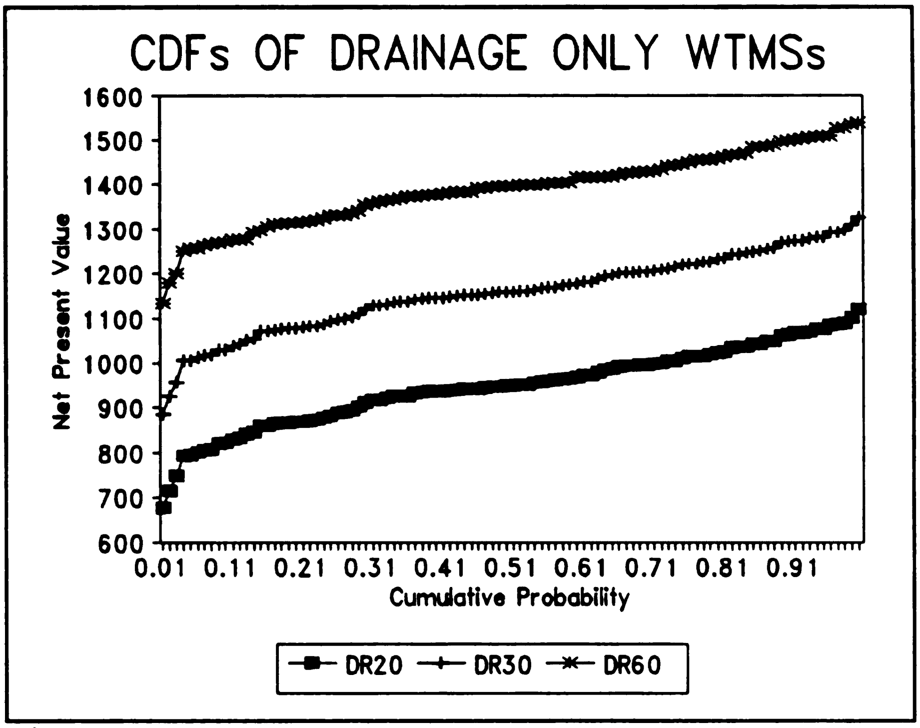


Figure 4.9.

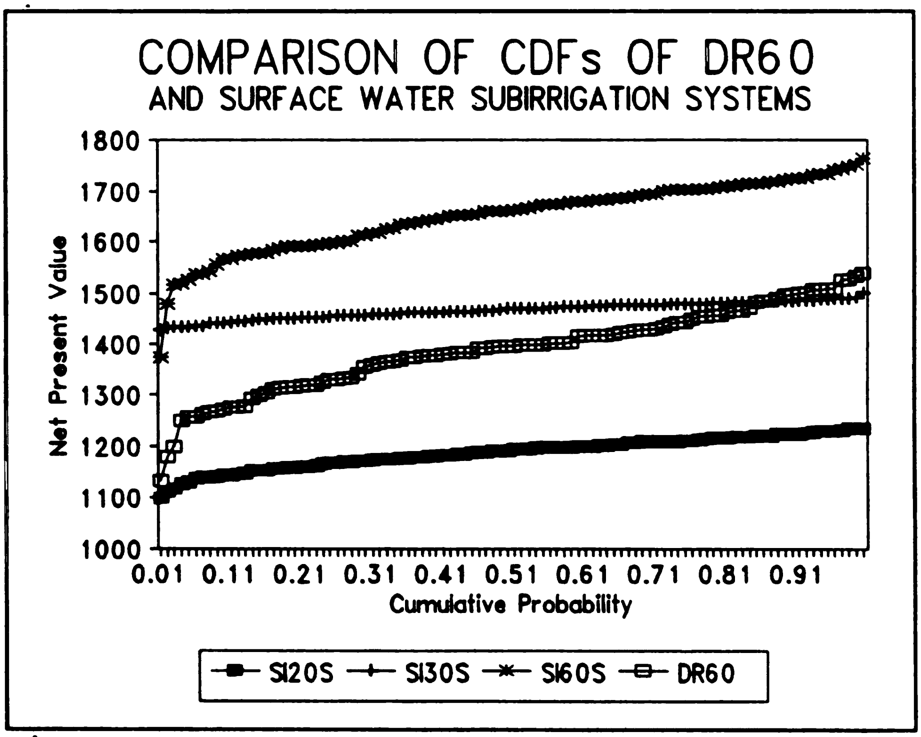


Figure 4.10.

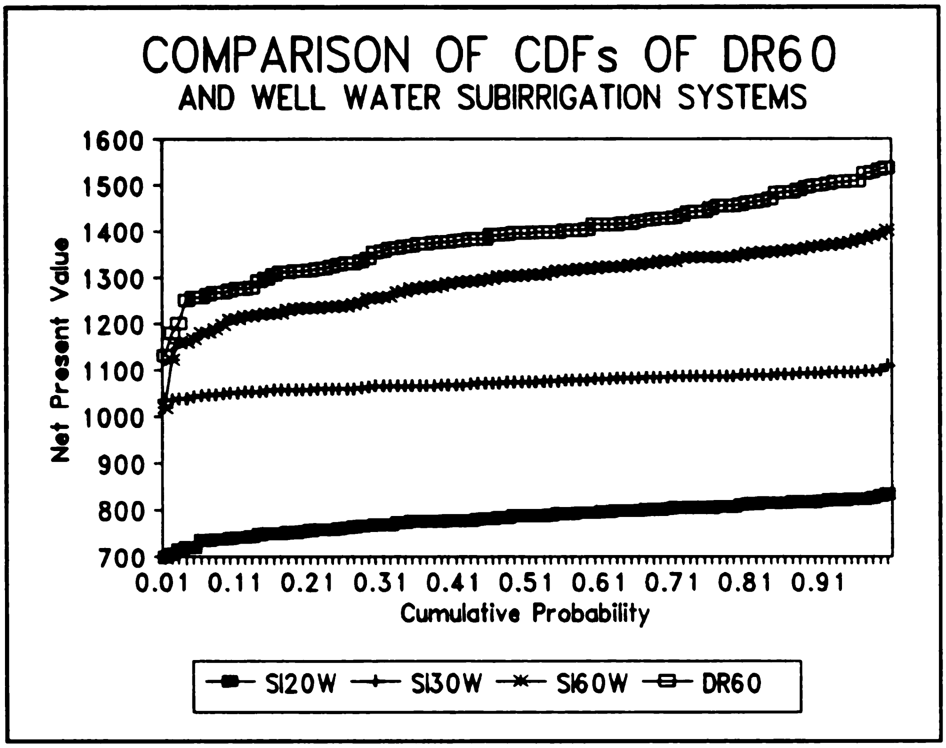


Figure 4.11

4.2.4. Stochastic Dominance with Respect to a Function Analysis

In order to discriminate farther between the two top-ranked systems, SI30S and SI60S, stochastic dominance with respect to a function was applied using Cochran and Raskin's GSD 3.0 program. The resulting risk aversion interval was adjusted to the scale of annual income from a 400 acre Huron County corn farm assuming a 4% real discount rate (following Raskin and Cochran, 1986). As a result, SI30S was found to be dominated by SI60S for all levels of absolute risk aversion less than .002. This implies that only a highly risk averse individual would prefer the more costly SI30S system when corn sells for $2.40/bushel.

4.3. Sensitivity Analysis

In the economic analysis, WTMSs have been compared by three methods: Basic NPV analysis, EV analysis, and stochastic dominance analysis. To simplify discussion in the sensitivity analysis, emphasis is placed on noting differences in the stochastic dominance relationship between DR60 and the subirrigation WTMS options under the base scenario (S0) and the adjusted scenarios. In certain cases, reference is made to changes in the absolute values of expected NPV. Table 4.7 shows the expected NPV and standard deviation of NPV of the WTMSs under the different sensitivity tests.

4.3.1. Sensitivity to Potential Yield

The first sensitivity test concerned the assumed potential yields. Under the base analysis, the potential yield under subirrigation (SPOTY) was assumed to be 180 bu/acre and that for drainage only 140 bu/acre (DPOTY). Several different combinations of assumed potential yields were run in the economic analysis to determine the "switching point," i.e., the point at which the dominance ordering changed such that DR60, the existing system, was no longer dominated by any of the other WTMSs as a result of changing the assumed potential yields. In all cases, when potential yields were changed, all necessary other changes in variable inputs and associated costs were also made.

In reducing the SPOTY from 180 bu/acre to 170 bu/acre while holding the DPOTY at 140 bu/acre (S8), or in keeping SPOTY at 180 bu/acre and increasing DPOTY to 150 bu/acre (S11), the only relationship that changed was between DR60 and SI30W. Whereas before SI30S dominated DR60 by SSD, under the new yield relationship between SPOTY and DPOTY, they could no longer be ordered by SSD.

In reducing SPOTY to 160 bu/acre but keeping DPOTY at 140 bu/acre (S9), the switching point occurred, meaning that DR60 was no longer dominated by either SI60S or SI30S by SSD criteria.

When the potential yields were brought even closer together so that SPOTY was set at 160 bu/acre and DPOTY was set at 150 bu/acre (S10), DR60 dominated all the subirrigation options by FSD.

These results indicate that the economic analysis is somewhat robust vis à vis the assumed differences in potential yields. A 10 bu/acre reduction in SPOTY was necessary to eliminate the dominance of SI30S over DR60 and a 20 bu/acre reduction in SPOTY was necessary to eliminate dominance of SI60S over DR60.

TABLE 4.7: Yield Sensitivity Analysis[3]

Water Table Management Investment Option	SPOTY = 170 DPOTY = 140		SPOTY = 160 DPOTY = 140		SPOTY = 160 DPOTY = 150		SPOTY = 180 DPOTY = 150	
	ENPV	SDNPV	ENPV	SDNPV	ENPV	SDNPV	ENPV	SDNPV
DR20	947	88	947	88	1065	95	1065	95
DR30	1156	88	1156	88	1274	94	1274	94
DR60	1389	82	1389	82	1508	88	1508	88
SI20S	1055	29	923	27	923	27	1187	31
SI30S	1331	15	1196	14	1196	14	1466	16
SI60S	1519	64	1389	60	1389	60	1650	68
SI20W	650	28	518	27	518	27	782	30
SI30W	938	16	803	15	803	15	1073	16
SI60W	1161	63	1031	60	1031	60	1292	67

[3] ENPV and SDNPV for the base analysis are included in Table 4.8.

4.3.2. Financial Parameter Sensitivity Analysis

A second set of sensitivity analyses of the economic results to changes in the assumed tax bracket (TB) and after-tax real rate of return (ATRR) revealed that the relationship among WTMSs does not change as the tax bracket is either decreased to 15% (S5) or increased to 31% (S6). However it does change with an increase in ATRR from 4% to 8% (S7). After increasing ATRR, SI60S maintained its position of dominance over DR60. But DR60 dominated all other subirrigation options by FSD after the change.

TABLE 4.8: Financial Parameter Sensitivity Analysis

Water Table Management Investment Option	ATTR = 8%		Tax Bracket TB = 15%		Tax Bracket TB = 31%		Base Analysis	
	ENPV	SDNPV	ENPV	SDNPV	ENPV	SDNPV	ENPV	SDNPV
DR20	446	67	1143	104	902	85	947	88
DR30	665	66	1377	104	1105	84	1156	88
DR60	904	62	1639	97	1331	79	1389	82
SI20S	470	22	1435	36	1130	29	1187	31
SI30S	734	11	1754	19	1400	15	1466	16
SI60S	936	51	1957	80	1579	65	1650	68
SI20W	79	21	975	36	738	29	782	30
SI30W	351	12	1308	19	1019	16	1073	16
SI60W	576	51	1553	79	1232	64	1292	67

4.3.3. Investment Cost and Output Price Sensitivity Analysis

Changes in the output price significantly changed the relationship among the WTMSs. At a lower output price of PC = \$1.80 (S2), which is the price farmers in the Saginaw Bay area are receiving for corn at the elevators after the 1992 harvest, DR60 dominates all WTMS options by FSD. In addition, the expected NPV of DR60 at the lower output price exceeds that of all other WTMSs. In fact, at the lower output price, only two of the subirrigation options, SI30S and SI60S, had positive ENPV.

At higher output prices this result is reversed. With PC = \$2.85/bu (S3) all of the surface water subirrigation options dominate DR60 by either FSD or SSD. For the well water subirrigation options, SI60W dominates DR60 by FSD and the pair SI30W - DR60 cannot be ordered by SSD.

For PC = \$3.00/bu (S4), which might be considered the upper bound on what farmers might expect to receive for their corn, DR60 is dominated by FSD or SSD by all possible subirrigation WTMS options except SI20W.

The minimum corn price at which a subirrigation system stochastically dominates the alternative of no investment is \$2.05/bu under FSD and \$2.00/bu under SSD. In both instances, SI60S is the dominant system.

TABLE 4.9: Output Price Sensitivity Analysis

Water Table Management Investment Option	Corn Price PC= $1.80/bu		Corn Price PC= $2.85/bu		Corn Price PC= $3.00/bu		Base Analysis	
	ENPV	SDNPV	ENPV	SDNPV	ENPV	SDNPV	ENPV	SDNPV
DR20	-5	58	1661	111	1900	118	947	88
DR30	202	58	1871	110	2110	118	1156	88
DR60	428	54	2109	103	2349	110	1389	82
SI20S	-123	20	2170	39	2498	42	1187	31
SI30S	138	11	2462	20	2795	22	1466	16
SI60S	351	44	2624	85	2948	91	1650	68
SI20W	-528	20	1765	38	2092	41	782	30
SI30W	-255	12	2069	20	2402	22	1073	16
SI60W	-7	44	2266	85	2591	91	1292	67

The final sensitivity analysis involved changing the values of certain costs associated with installing a subirrigation system. The installation cost estimates were based on estimates from drainage/subirrigation contractors, pump distributors, and well drilling firms. The costs given for drilling a well and for buying and installing the pumping system varied widely, while costs for other system components, including drainage tile and control structure installation varied only within a small range. To judge the sensitivity of the economic results to the values used in the base analysis, the cost of the well and pump were varied separately and then together.

From conversations with drilling firm representatives, the cost of drilling an irrigation well can vary from $10,000 to $25,000, depending on the specific drilling conditions. A figure of $15,000 for well drilling was used in the base analysis. Under the base analysis, all of the three WTMSs with a well water source (SI20W, SI30W, and SI60W) were dominated by DR60 by FSD. If a well drilling cost of $10,000 is used in the economic analysis instead of $15,000 (S14), SI60W and DR60 can no longer be ordered by SSD while DR60 maintains its position vis à vis the other two well water subirrigation systems, showing that economic results are only slightly sensitive to the assumed cost of the well in the base analysis.

The pump installation costs used in the base analysis were quoted by contractors, but appeared to be somewhat inflated, based on figures quoted by the Huron County extension agent, James LeCureux, who is familiar with pump prices paid by certain farmers in the county. If the pump installation costs are reduced by 50% and the economic analysis rerun (S13), the results change only slightly. SI60W and DR60 can no longer be ordered by SSD whereas under the base scenario, DR60 dominated SI60W FSD. The position of DR60 vis à vis the other WTMSs in the altered analysis remains the same as in the base analysis.

If both the pump and well costs are reduced together (S15), the basic relationship among the WTMSs changes more noticeably. SI30S dominates DR60 by FSD instead of SSD and SI60W dominates DR60 by FSD, reversing the relationship between these two options compared with the base analysis. SI30W and DR60 can no longer be ordered by SSD under this scenario.

The result of the cost sensitivity analysis confirm that the economic analysis is relatively robust to changes in certain key cost parameters. Under all circumstances, changing the cost of inputs changes the expected NPV of the various options, but rarely are the relationships among the various WTMSs significantly changed.

TABLE 4.10: Investment Cost Sensitivity Analysis

Water Table Management Investment Option	Pump Cost = 50% of Base		Well Cost = $10,000		Well & Pump Costs Lower		Base Analysis	
	ENPV	SDNPV	ENPV	SDNPV	ENPV	SDNPV	ENPV	SDNPV
DR20	947	88	947	88	947	88	947	88
DR30	1156	88	1156	88	1156	88	1156	88
DR60	1389	82	1389	82	1389	82	1389	82
SI20S	1237	31	1187	31	1237	31	1187	31
SI30S	1516	16	1466	16	1516	16	1466	16
SI60S	1699	68	1650	68	1699	68	1650	68
SI20W	846	30	882	30	947	30	782	30
SI30W	1140	16	1173	16	1238	16	1073	16
SI60W	1356	67	1392	67	1457	67	1292	67

In summary, the ranking of alternative WTMS investment options by stochastic dominance criteria is most sensitive to changes in yield response, output price, and after-tax real rate of return. It is less sensitive to financial parameters such as the tax bracket and the fixed cost of the irrigation pump and well.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1. Summary

This study set out to evaluate alternative water table management system (WTMS) investments. The strategies evaluated include converting an existing drainage-only system at 60-ft tile spacings into a subirrigation/drainage system at the same 60-ft spacing (SI60S and SI60W), reducing the drain spacing to 20 feet and 30 feet in a drainage-only system (DR20, DR30), and reducing the drain spacing to 20 feet and 30 feet in a subirrigation/drainage system (SI20S, SI30S, SI20W, SI30W). For each of the subirrigation options, two different water supplies were considered, a well water supply and a surface water supply.

The particular strategies chosen for analysis reflect actual conditions in Huron County and the other counties in the Saginaw Bay area. Many farmers are improving their existing drainage systems by "splitting the tiles," i.e., reducing the spacing between the drains by adding an additional tile line or more between two existing drainage tiles. Typically, the drain spacing in the area is 60 to 66 feet. Thus farmers are reducing this spacing, usually to 30 feet. But some farmers who are installing new systems are spacing the drains at 20 to 25 feet. Reducing the spacing between drainage tiles improves uniformity of drainage and allows farmers to get onto their fields in the spring for planting and in the fall for harvest. Other farmers in the area are retrofitting their drainage systems from drainage-only systems to subirrigation systems. This study looked at whether investing in a WTMS is likely to provide enough additional benefit to offset the cost of the investment.

One other issue of interest was how much financial benefit the dominant surface water subirrigation strategy might generate toward financing an irrigation district to bring water from Lake Huron to farmers' fields. This is an important issue because a large number of acres in Huron County that are otherwise highly suitable for subirrigation do not have a sufficient water supply.

A simulation model, DRAINMOD, was used to generate yield and irrigation application amounts for 33 years of historic weather data from Flint, Michigan. DRAINMOD was chosen as the simulation model in the yield analysis because it captures the effect of both excess and deficient water stress on corn yields and it is specifically designed to study these effects under both subirrigation and drainage at different drain spacings. For these reasons it was an ideal choice for the present analysis. However, validation of the yield component of the model proved difficult because there was insufficient field data at a site where a long enough series of hourly rainfall data existed. Using the Flint weather data and historic corn yields for Genesee County, DRAINMOD tracked fairly well the fluctuations in yield. Using Flint weather and historic farm-level corn yield data, DRAINMOD performed less well. When DRAINMOD's output was compared with the daily weather for the Flint station, an agrometeorologist judged the predicted yield results to be realistic.

In the first stage of the economic analysis, DRAINMOD yield and irrigation application amounts for the base weather sequence (1958-87) were used in conjunction with investment, operating, and production cost data to calculate net present values for a 30-year planning horizon.

Results of the NPV analysis revealed that two of the three surface water subirrigation options, SI30S and SI60S, and one of the well water subirrigation options, SI60W, had higher NPV than the existing 60-ft drainage-only option. However, the existing system dominated the remaining subirrigation options and the two narrower spacing drainage-only options. The annualized gross margins for the dominant subirrigation systems over the existing system were $11/acre for SI30S, $21/acre for SI60S, and $3/acre for SI60W.

The base NPV analysis provided a measure of what a farmer could expect the NPV of the investment options to look like under the base weather sequence. But it did not answer the larger question of what a farmer could expect under different weather sequences. Application of Monte Carlo simulation techniques provided this extra insight. From the distribution of NPVs generated by drawing randomly one hundred 30-year sequences of weather-yield outcomes, expected net present values (ENPV) and standard deviations of net present value (SDNPV) were calculated. The ENPV gives a measure of how a farmer can expect the NPV of the investment alternatives to look given one hundred possible 30-year sequences of weather and the SDNPV provides insight into the variability of ENPV.

Comparison of the NPV and ENPV results showed that under the base weather sequence, the subirrigation systems fared much better than under the randomized weather sequences. In all cases the NPV of subirrigation options was more than $100 greater than the ENPV of the same option. Looking only at ENPV and ignoring SDNPV initially, only the two surface water subirrigation systems at the wider drain spacings, SI30S and SI60S, had higher ENPVs than the existing system. SI30S had an annualized gross margin of $4/acre and SI60S had an annualized gross margin of $19/acre over the existing system.

For the dominant surface water subirrigation system, SI60S, the figure of $19/acre could be interpreted as the on-farm benefit of subirrigation and could be used as a measure of the willingness to pay a water use fee in an irrigation district. However, this figure would have to be considered an upper bound because in the cost calculations, labor costs and fixed costs such as insurance, land rent, and any depreciation and interest costs not associated with the WTMS investment itself were not included.

Bringing the SDNPV back into the picture, application of EV efficiency criteria across investment options revealed that the same two surface water subirrigation strategies, SI30S and SI60S dominate the conventional 60-ft drainage-only system, DR60, The dominant strategies have both higher ENPVs and lower SDNPVs than the conventional system. Between SI30S and SI60S dominance could not be established under EV criteria. For circumstances where a surface water source is unavailable, neither could dominance between DR60 and SI60W be established using EV efficiency criteria because between the two there is a tradeoff between higher ENPV and higher variability of ENPV. DR60 has a higher ENPV of $1,389 compared with $1,292 for SI60W, but it also has a higher SDNPV of $82 compared with $67. Thus bringing standard deviations into the decision framework, SI60W remained in the efficient set with DR60, as had been the case in the base NPV analysis.

Application of first and second degree stochastic dominance (FSD and SSD) criteria identified a narrower choice set than the EV approach indicated: SI30S and SI60S still could not be ordered and both still dominated DR60, SI60S by FSD and SI30S by SSD criteria. But using SSD criteria, DR60 dominated SI60W, whereas using EV efficiency criteria, the two could not be ordered.

In order to discriminate between the two top-ranked systems, SI30S and SI60S, stochastic dominance with respect to a function was applied and SI30S was found to be dominated by SI60S for all levels of absolute risk aversion less than .002, based on whole-farm annual net income. This implies that only a highly risk averse individual would prefer the more costly SI30S system.

Sensitivity of the economic results to changes in yield assumptions, output price, cost assumptions and certain financial parameters was tested by varying these key parameters. The first sensitivity test concerned the assumed potential yields. Under the base analysis, the potential yield under subirrigation (SPOTY) was assumed to be 180 bu/acre and that for drainage only 140 bu/acre (DPOTY). A 10 bu/acre difference in either SPOTY or DPOTY eliminated the dominance of SI30S over DR60 and a 20 bu/acre reduction in SPOTY eliminated dominance of SI60S over DR60. The dominance ordering between both pairs was reversed completely when SPOTY was set at 160 bu/acre and DPOTY was set at 150 bu/acre. These results indicate that the economic analysis is only modestly robust vis à vis the assumed differences in potential yields.

Changes in the assumed output price also significantly changed the stochastic dominance relationship among the investment options. Lower output prices favored DR60 and higher output prices favored the subirrigation options. At a price of $1.80/bu DR60 is no longer dominated by any of the subirrigation options. The minimum corn price at which a subirrigation system stochastically dominated DR60 was $2.05/bu under

FSD and $2.00 under SSD. In both instances, SI60S was the dominant system. At the higher prices, all the subirrigation option except SI20W dominated DR60.

Of the financial parameters tested, changing the tax bracket used in the analysis did not affect the stochastic dominance relationship among the various options; however, changing the after-tax real rate of return (ATRR) did. Increasing ATRR from 4% to 8% skewed the results in favor of DR60, the existing system. After the change, DR60 dominated all of the subirrigation options by FSD, except SI60S, which still dominated DR60 by FSD. The economic results were robust to changing cost assumptions about the pump and well.

5.2. Conclusions

This economic analysis of water table management investment options identified two subirrigation options as dominating the existing drainage-only system (DR60) under conditions of certainty and of risk. These were both surface water subirrigation systems, one with tile spacings at 30 feet (SI30S) and the other at 60 feet (SI60S). SI60S had an annualized gross ENPV of $19/acre over DR60. This figure could be used as a measure of the on-farm benefit of subirrigation for continuous corn production and hence as an upper bound on farmers' willingness to pay to obtain a surface water supply (e.g., by participating in an irrigation district).

In considering the two surface water subirrigation options, a farmer would have to be extremely risk averse to choose the narrower spaced option, SI30S. The 60-ft tile spacing option, SI60S, had an annualized ENPV $15/acre higher than SI30S. Its SDNPV was also $3/acre higher (in annualized terms); however, the difference in ENPV between the two was larger enough that even moderately risk averse farmers would still choose SI60S over SI30S.

None of the well water source subirrigation systems dominated the existing system and neither did the narrower spaced drainage-only options. These results suggest that the additional investment costs of drilling a well and the higher pumping costs associated with deep well pumping offset the benefit of higher and more stable subirrigated yields and that the additional cost of investing in improved drainage on a Kilmanagh soil may not produce enough additional yield benefit to offset the investment costs. These results held under both assumptions of certainty and of risk.

All of the economic findings in this analysis are valid under the assumption that continuous corn is being produced on the 40 acre field. In the Saginaw Bay area, the actual practice is to rotate some combination of corn, soybeans, beets, and dry beans. Including an appropriate rotation in the economic analysis would have to be done to gain a true appreciation of the economic outcome of investing in a water table management system. It is a limitation of the current study that these other crops could not be included due to time constraints.

However, based on the results of other economic studies reviewed here (LeCureux and Booms, 1990a-d; LeCureux, 1991a,b) it appears that returns to subirrigation of a rotation including sugar beets would be higher than for a continuous corn production regime because subirrigated sugar beets produce a substantial net yield and net revenue benefit over drainage-only sugar beets at recent prices. For the other two crops commonly in the rotation, soybeans and dry beans, the results are mixed. Some years they yield a positive net revenue benefit to subirrigation and some years the benefit is negative (LeCureux and Booms, 1990b; LeCureux, 1991a,b). If we assume their net contribution to the rotation is zero, including a profitable crop like sugar beet in the economic analysis of subirrigation under rotation would have to increase the net revenue benefit of the rotation over the continuous corn regime and hence the returns to subirrigation. Future research will have to look at the broader issue of the profitability of WTMS investments under a rotation.

The economic results are also sensitive to the assumed corn price. The minimum corn price at which a subirrigation option, SI60S, dominated the existing drainage-only system was $2.00/bu under SSD. If it were anticipated that corn prices were to remain below $2.00/bu in the future, farmers should not consider improving their water table management system. If, on the other hand, it is anticipated that corn prices will be higher than $2.00/bu, the surface water source subirrigation options at the wider drain spacings would provide farmers with higher net returns than their existing drainage-only system if surface water were available for irrigation at no extra cost. If corn prices were as high as $2.85-$3.00/bu, even the well water options at the 30- and 60-ft tile spacings would become more profitable than the existing system. Only at a $3.00/bu corn price would the on-farm benefit of subirrigation at 60-ft tile spacings using surface water (SI60S) produce enough additional benefit to offset water use fees as high as $35/acre. The necessary corn price to produce an additional on-farm benefit of $25/acre over the existing system would be $2.70/bu.

Another issue that future research will have to consider is the environmental spillover effects of alternative water table management investment options. Current research on these effects should provide the necessary data to conduct such an analysis.

APPENDIX A

BASIC CODE FOR MONTE CARLO SIMULATION FOR E[NPV] AND SD[NPV] CALCULATIONS FOR WTMS ANALYSIS

```
DEFINT I-N

'INITIALIZATION OF MODEL PARAMETERS

POUT = 2.4                          'corn price in $/bu
TB = .28                            'tax bracket
ATRR = .04                          'after-tax real return
OCI = .105                          'interest on operating capital
NRUNS = 100                         'number of simulation runs
NWTMS = 9                           'number of WTMS options
NYRS = 33                           'number of years of weather data
NNPV = 30                           'number of loops for NPV calculation
PBC = .57                           'summary variable of all per
                                    'bushel costs, including drying
                                    'cost, harvesting fuel cost,
                                    'trucking/freight cost, and
                                    'marketing cost.

OPEN "C:\123\DATA\MONTE12A.OUT" FOR OUTPUT AS #1
OPEN "C:\123\DATA\MONTE12B.OUT" FOR OUTPUT AS #2
OPEN "C:\123\DATA\MONTE12C.OUT" FOR OUTPUT AS #3

'DIMENSIONING OF ARRAYS
DIM XNPVRUN(NRUNS)                  'Array for NPV in the Monte Carlo
                                    'simulation.
DIM D2(NYRS, 2)                     'Yield and volume associated with
DIM D3(NYRS, 2)                     'different WTMS.
DIM D6(NYRS, 2)                     'D2 = drainage: 20-ft tile spacing.

DIM S2(NYRS, 2)                     'S2 = subirrigation 20 ft spacing.
DIM S3(NYRS, 2)                     'etc.
DIM S6(NYRS, 2)

DIM A(NYRS, 2)
DIM YR(NYRS)                        'Array of years 1958-90.

DIM SDNPV(NWTMS), ENPV(NWTMS)       'Arrays used in the SDNPV and ENPV
                                    'calculations.
DIM COUNT(7)                        'Array for histograms.
DIM K(NNPV * NRUNS)                 'Array for storing the random #s.


'ARRAYS OF COSTS ASSOCIATED WITH THE DIFFERENT INVESTMENT OPTIONS
'SEE BELOW FOR DEFINITIONS. IN ALL CASES, WTMS = WATER TABLE MGT SYSTEM

DIM CWTMS(NWTMS), PWAT(NWTMS), VPC(NWTMS), POTY(NWTMS)

DIM DWELL(NWTMS), DPUMP(NWTMS), DTILE(NWTMS), DCS(NWTMS)

'VALUES FOR THE CWTMS = Initial Investment Cost for Each Investment
'Alternative (converted to $/acre figures).

DATA 527, 269, 0, 944, 687, 435, 1339, 1082, 830
```

```
FOR IA = 1 TO NWTMS
READ CWTMS(IA)
NEXT IA

'VALUES FOR PWAT = Price of Water (converted to $/acre-cm)
DATA 0, 0, 0, 0.59, 0.59, 0.59, 0.89, 0.89, 0.89

FOR IA = 1 TO NWTMS
READ PWAT(IA)
NEXT IA

'VALUES FOR VPC = Variable Production Costs ($/acre)
DATA 105, 105, 105, 128, 128, 128, 128, 128, 128

FOR IA = 1 TO NWTMS
READ VPC(IA)
NEXT IA

'VALUES FOR POTY = Potential Yield (bu/acre)
DATA 140, 140, 140, 180, 180, 180, 180, 180, 180

FOR IA = 1 TO NWTMS
READ POTY(IA)
NEXT IA

'VALUES FOR DWELL = Depreciation on the Well for years 1-15 ($/acre)
DATA 0, 0, 0, 0, 0, 0, 25, 25, 25

FOR IA = 1 TO NWTMS
READ DWELL(IA)
NEXT IA

'VALUES FOR DPUMP = Pump Depreciation Pump, years 1-7 and 16-22 ($/acre)
DATA 0, 0, 0, 16.43, 16.43, 16.43, 19.28, 19.28, 19.28

FOR IA = 1 TO NWTMS
READ DPUMP(IA)
NEXT IA


'VALUES FOR DTILE = Depreciation on the Tile for years 1-15 ($/acre)
DATA 35, 18, 0, 52, 34, 18, 52, 34, 18

FOR IA = 1 TO NWTMS
READ DTILE(IA)
NEXT IA

'VALUES FOR DCS = Control Structure Depreciation, years 1-15 ($/acre)
DATA 0, 0, 0, 4, 4, 4, 4, 4, 4

FOR IA = 1 TO NWTMS
READ DCS(IA)
NEXT IA

'VALUES FOR OCCS = Operating Costs for Control Structure ($/acre)
DATA 0, 0, 0, 0.04, 0.04, 0.04, 0.04, 0.04, 0.04

FOR IA = 1 TO NWTMS
READ OCCS(IA)
NEXT IA
```

```
'VALUES FOR OCP = Operating Costs Associated with Pump
DATA 0, 0, 0, 0.83, 0.83, 0.83, 0.98, 0.98, 0.98

FOR IA = 1 TO NWTMS
READ OCP(IA)
NEXT IA

'VALUES FOR PLABOR = Labor Cost for Irrigation ($/acre)
DATA 0, 0, 0, 3.4, 3.4, 3.4, 3.4, 3.4, 3.4

FOR IA = 1 TO NWTMS
READ PLABOR(IA)
NEXT IA

'VALUES FOR RPUMP = Replacement Cost for Pump Falls in Year 16 ($/acre)
DATA 0, 0, 0, 30, 30, 30, 50, 50, 50

FOR IA = 1 TO NWTMS
READ RPUMP(IA)
NEXT IA

'VALUES FOR THE YR MATRIX
DATA 1958, 1959, 1960, 1961, 1962, 1963, 1964, 1965, 1966
DATA 1967, 1968, 1969, 1970, 1971, 1972, 1973, 1974, 1975
DATA 1976, 1977, 1978, 1979, 1980, 1981, 1982, 1983, 1984
DATA 1985, 1986, 1987, 1988, 1989, 1990

FOR I = 1 TO NYRS
        READ YR(I)
NEXT I

'VALUES FOR THE D2 MATRIX

DATA 100.0, 75.9, 84.0, 96.8, 100.0
DATA 52.8, 100.0, 69.7, 93.6, 99.6
DATA 100.0, 100.0, 100.0, 100.0, 100.0
DATA 100.0, 73.8, 100.0, 99.6, 100.0
DATA 60.1, 100.0, 100.0, 99.7, 100.0
DATA 98.6, 86.8, 100.0, 100.0, 65.0
DATA 59.8, 100.0, 100.0
DATA 0, 0, 0, 0, 0
DATA 0, 0, 0, 0, 0
DATA 0, 0, 0, 0, 0
DATA 0, 0, 0, 0, 0
DATA 0, 0, 0, 0, 0
DATA 0, 0, 0, 0, 0
DATA 0, 0, 0

FOR JE = 1 TO 2
        FOR IE = 1 TO NYRS
        READ D2(IE, JE)
        NEXT IE
NEXT JE

'VALUES FOR THE D3 MATRIX
DATA 100., 76.7, 84.5, 97.0, 100.0
DATA 52.9, 100.0, 70.1, 94.0, 99.6
DATA 100., 100.0, 100., 100., 100.
DATA 100.0, 74.0, 100.0, 99.6, 100.0
DATA 60.5, 100.0, 100.0, 99.8, 100.0
DATA 98.8, 87.1, 100.0, 100.0, 65.2
DATA 59.9, 100.0, 100.0
```

```
DATA 0., 0., 0., 0., 0.
DATA 0., 0., 0., 0., 0.
DATA 0., 0., 0., 0., 0.
DATA 0., 0., 0., 0., 0.
DATA 0., 0., 0., 0., 0.
DATA 0., 0., 0., 0., 0.
DATA 0., 0., 0.

FOR JE = 1 TO 2
        FOR IE = 1 TO NYRS
        READ D3(IE, JE)
        NEXT IE
NEXT JE

'VALUES FOR THE D6 MATRIX
DATA 100.0, 82.2, 86.3, 97.9, 100.0
DATA 55.6, 100.0, 72.4, 95.3, 99.6
DATA 100.0, 95.9, 100.0, 100.0, 100.0
DATA 100.0, 76.1, 100.0, 98.0, 100.0
DATA 63.1, 100.0, 100.0, 100.0, 100.0
DATA 99.9, 90.2, 100.0, 100.0, 67.2
DATA 61.5, 100.0, 100.0
DATA 0, 0, 0, 0, 0
DATA 0, 0, 0, 0, 0
DATA 0, 0, 0, 0, 0
DATA 0, 0, 0, 0, 0
DATA 0, 0, 0, 0, 0
DATA 0, 0, 0, 0, 0
DATA 0, 0, 0

FOR JE = 1 TO 2
        FOR IE = 1 TO NYRS
        READ D6(IE, JE)
        NEXT IE
NEXT JE

'VALUES FOR THE S2 MATRIX
DATA 100.0, 93.8, 100.0, 100.0, 99.9
DATA 100.0, 99.1, 100.0, 100.0, 98.0
DATA 82.0, 92.2, 95.0, 99.9, 91.5
DATA 100.0, 99.0, 97.5, 85.6, 99.9
DATA 100.0, 91.5, 92.7, 100.0, 100.0
DATA 98.0, 100.0, 100.0, 100.0, 100.0
DATA 100.0, 100.0, 100.0
DATA 16.92, 20.78, 20.71, 19.15, 18.37
DATA 26.31, 19.06, 24.36, 24.95, 19.25
DATA 17.06, 14.32, 16.91, 19.92, 15.12
DATA 20.46, 19.33, 19.27, 20.57, 18.97
DATA 24.06, 19.89, 15.57, 18.40, 18.67
DATA 20.69, 22.00, 19.79, 17.24, 27.73
DATA 27.69, 16.25, 18.18

FOR JE = 1 TO 2
        FOR IE = 1 TO NYRS
        READ S2(IE, JE)
        NEXT IE
NEXT JE
```

```
'VALUES FOR THE S3 MATRIX

DATA 100.0, 96.0, 100.0, 100.0, 99.7
DATA 100.0, 100.0, 100.0, 100.0, 98.8
DATA 91.9, 94.3, 95.0, 100.0, 93.1
DATA 100.0, 96.7, 99.9, 98.2, 100.0
DATA 100.0, 99.5, 99.7, 100.0, 100.0
DATA 99.6, 100.0, 100.0, 100.0, 100.0
DATA 100.0, 99.7, 100.0
DATA 14.40, 17.70, 19.24, 16.60, 14.97
DATA 23.81, 15.46, 22.42, 22.36, 16.14
DATA 13.51, 10.50, 13.78, 16.45, 12.27
DATA 17.76, 17.74, 15.70, 17.65, 15.42
DATA 22.08, 16.60, 12.39, 14.95, 15.94
DATA 17.09, 18.80, 16.93, 13.83, 25.53
DATA 25.41, 12.07, 15.66

FOR JE = 1 TO 2
        FOR IE = 1 TO NYRS
        READ S3(IE, JE)
        NEXT IE
NEXT JE

'VALUES FOR THE S6 MATRIX

DATA 100.0, 100.0, 100.0, 100.0, 99.7
DATA 86.1, 100.0, 96.9, 96.8, 99.7
DATA 97.5, 95.9, 100.0, 100.0, 99.8
DATA 100.0, 90.2, 100.0, 98.0, 100.0
DATA 94.8, 100.0, 100.0, 100.0, 100.0
DATA 100.0, 100.0, 100.0, 100.0, 68.6
DATA 64.9, 100.0, 100.0
DATA 7.83, 9.31, 11.10, 10.17, 7.27
DATA 9.89, 8.06, 11.03, 10.36, 8.54
DATA 6.17, 4.24, 7.37, 10.40, 6.86
DATA 9.38, 9.97, 7.35, 8.85, 9.38
DATA 10.61, 9.38, 7.00, 9.02, 9.33
DATA 9.13, 10.02, 10.20, 7.44, 7.38
DATA 3.80, 5.46, 9.14

FOR JE = 1 TO 2
        FOR IE = 1 TO NYRS
        READ S6(IE, JE)
        NEXT IE
NEXT JE

PRINT #1, "                              BASE SCENARIO"
PRINT #1, " MONTE CARLO SIMULATION TO GENERATE ENPV, SDNPV OF OPTIONS"
PRINT #2, " HISTOGRAM GENERATION FOR ALTERNATIVE WTMS INVESTMENTS"
PRINT #3, " MONTE CARLO SIMULATION TO GENERATE CDFS OF WTMS INVESTMENTS"


'OUTERMOST LOOP - CONDITIONS FOR EACH WTMS ARE INITIALIZED

FOR IA = 1 TO NNPV * NRUNS            'Creates an Array of 3000 Random
   R = RND                            'Numbers from 1-33 which are used
   N = (NYRS - 1) * R                 'in referencing a yield, volume
   K(IA) = FIX(N) + 1                 'pair for the Monte Carlo runs.
NEXT IA
```

```
FOR IA = 1 TO NWTMS                'For each WTMS, the correct yield,
        FOR JE = 1 TO 2            'volume matrix is chosen for the
                FOR IE = 1 TO NYRS 'NPV calculations.
                IF IA = 1 THEN A(IE, JE) = D2(IE, JE)
                IF IA = 2 THEN A(IE, JE) = D3(IE, JE)
                IF IA = 3 THEN A(IE, JE) = D6(IE, JE)
                IF IA = 4 OR IA = 7 THEN A(IE, JE) = S2(IE, JE)
                IF IA = 5 OR IA = 8 THEN A(IE, JE) = S3(IE, JE)
                IF IA = 6 OR IA = 9 THEN A(IE, JE) = S6(IE, JE)
                NEXT IE
        NEXT JE

PWAT = PWAT(IA)                    'Selects correct prices and costs
VPC = VPC(IA)                      'for alternate WTMSs.
POTY = POTY(IA)
CWTMS = CWTMS(IA)
OCCS = OCCS(IA)
OCP = OCP(IA)
TOT = 0                            'Sums NPVs for ENPV calculations.
TDIFF = 0                          'Difference between NPV and ENPV for
                                   'SD calculations.

FOR I = 1 TO 7                     'Resets count to zero for histogram
        COUNT(I) = 0               'percentages.
NEXT I

FOR I = 1 TO NWTMS                 'Resets ENPV to zero before
        ENPV(I) = 0                'each WTMS.
NEXT I

FOR I = 1 TO NWTMS                 'Resets SDNPV to zero before
        SDNPV(I) = 0               'each WTMS.
NEXT I


PRINT #1, "WTMS"; IA
PRINT #2, "WTMS"; IA

'MONTE CARLO LOOP

FOR I1 = 1 TO NRUNS

'RESET XNPV, XNR, DNR, SUM1 AND DF TO ZERO BEFORE EACH SIMULATION

XNPV = -CWTMS                      'initial cost WTMS (year zero)
XNR = 0                            'undiscounted net revenue
DNR = 0                            'discounted net revenue
SUM1 = 0                           'first sum in NPV calculation
SUM2 = 0                           'second sum in NPV calculation
DF = 0                             'discount factor

'INNERMOST LOOP FOR CALCULATING NPV OVER A 30-YEAR INVESTMENT HORIZON

FOR M = 1 TO NNPV                  'Establishes correct depreciation
                                   'periods for pump, well, tile, CS.
        IF M <= 7 THEN
                DPUMP = DPUMP(IA)
        ELSEIF M > 7 AND M <= 15 THEN
                DPUMP = 0
        ELSEIF M > 15 AND M <= 22 THEN
                DPUMP = DPUMP(IA)
```

```
        ELSE
                DPUMP = 0
        END IF
        IF M <= 15 THEN DCS = DCS(IA) ELSE DCS = 0
        IF M <= 15 THEN DWELL = DWELL(IA) ELSE DWELL = 0
        IF M <= 15 THEN DTILE = DTILE(IA) ELSE DTILE = 0
        IF M = 16 THEN RPUMP = RPUMP(IA) ELSE RPUMP = 0

PLACE% = ((I1 * NNPV) - NNPV) + M   'References an element in the yield
RYLD = A(K(PLACE%), 1) / 100        'volume matrix.
VOL = A(K(PLACE%), 2)
YEAR = YR(M)

YLD = RYLD * POTY                   'conversion of rel yld to bu/acre
VPBC = YLD * PBC                    'variable per bushel
                                    'production costs
VIC = VOL*PWAT+OCCS+OCP+PLABOR      'variable cost of irrigation

SUM1 = (POUT * YLD - VIC - VPC - VPBC - DWELL - DPUMP - DCS - DTILE -
OCI * (VIC + VPC + VPBC)) * (1 - TB)
SUM2 = DWELL + DPUMP + DCS + DTILE  'Depreciation cost, which are
XNR = SUM1 + SUM2 - RPUMP           'subtracted out in SUM1 for tax
DF = (1 + ATRR) ^ M                 'purposes must be added back in
DNR = XNR / DF                      'to reflect actual cash flow.
XNPV = XNPV + DNR

NEXT M

'END OF NPV LOOP

XNPVRUN(I1) = XNPV                  'Array of NPV for prob dist.

TOT = TOT + XNPV                    'For ENPV calculations.

NEXT I1

'END OF MONTE CARLO LOOP

ENPV(IA) = TOT / NRUNS              'Array of ENPV for all WTMSs

FOR I = 1 TO NRUNS                  'Calculation of SD
        DIFF = (XNPVRUN(I) - ENPV(IA)) ^ 2
        TDIFF = TDIFF + DIFF
NEXT I

SDNPV(IA) = (TDIFF / NRUNS) ^ .5    'Array of SD for all WTMSs

PRINT #1, ""
PRINT #1, USING " ENPV  = $$####"; ENPV(IA);
PRINT #1, USING " SDNPV = $$####"; SDNPV(IA)
PRINT #1, ""

'CALCULATION OF HISTOGRAM VALUES
'DETERMINING MAX AND MIN VALUES OF NPV (SPREAD)

XMINVAL = XNPVRUN(1)
XMAXVAL = XNPVRUN(1)

FOR I = 1 TO NRUNS
IF XNPVRUN(I) < XMINVAL THEN XMINVAL = XNPVRUN(I)
IF XNPVRUN(I) > XMAXVAL THEN XMAXVAL = XNPVRUN(I)
NEXT I
```

```
PRINT #2, USING "MINIMUM VALUE = #####"; XMINVAL
PRINT #2, USING "MAXIMUM VALUE = #####"; XMAXVAL

DIM HIST(7)
BARWIDTH = (XMAXVAL - XMINVAL) / 7

PRINT #2, ""
PRINT #2, USING "BARWIDTH: ###"; BARWIDTH

FOR I = 1 TO 7
HIST(I) = XMINVAL + BARWIDTH * (I - 1)
NEXT I

PRINT #2, "LOWER LIMITS ON HISTOGRAM BARS"
FOR I = 1 TO 7
PRINT #2, "BAR"; I;
PRINT #2, USING "LOWER LIMIT: ####"; HIST(I)
NEXT I

FOR J = 1 TO NRUNS
I = 8
100 I = I - 1
IF XNPVRUN(J) >= HIST(I) THEN COUNT(I) = COUNT(I) + 1 ELSE 100
NEXT J

PRINT #2, "HISTOGRAM: PERCENTAGES IN EACH BAR:"
FOR I = 1 TO 7
PRINT #2, "PERCENTAGE IN BAR"; I; (COUNT(I) / NRUNS)
NEXT I

'SORT TREATMENTS BY NPV IN DESENDING ORDER

DO
  SWAPS% = FALSE%
  FOR I = 1 TO (NRUNS - 1)
    IF XNPVRUN(I) < XNPVRUN(I + 1) THEN
      SWAP XNPVRUN(I), XNPVRUN(I + 1)
      SWAPS% = I
    END IF
  NEXT I
LOOP WHILE SWAPS%

PRINT #3, "Full sort results are for WTMS"; IA; ": "
FOR I = 1 TO NRUNS
PRINT #3, USING "#####"; XNPVRUN(I)
NEXT I
NEXT IA

'END OF OUTERMOST LOOP

END
```

APPENDIX B

DRAINMOD DATA INPUTS

```
*****************************************************************************
                              d r a I n m o d

                 version: north carolina micro 4.05
             Last update: sept 1991
                language: ms fortran v 5.0

          Copyright (c) 1990, north carolina state university
                         all rights reserved

       Drainmod is a field-scale hydrologic model developed for
       the design of subsurface drainage systems. The model was
       developed by researchers at the dept. of biological and
       agricultural engineering, north carolina state university
       under the direction of R. W. Skaggs.

*****************************************************************************

                   *******************
                   * D r a I n m o d *
                   *******************

  data read from input file: c:\dm40\input40\dr2k12.Lis

                        title of run
                        ************

 dr, 20 ft tile spacing, kilmanagh soil = kilmancm, flint weather,
 dry slope 1.05, Wet slope = .68, Sf = 1.25, Plant days = 8, 1958-90


                       climate inputs
                       ******* ******

     description                               (variable)     value
-----------------------------------------------------------------------
 file for raindata .............  C:\dm40\weather\fnt5891.Rai
 file for temperature/pet data ..  C:\dm40\weather\fnt5890.Tem

 rainfall station number.........................(Rainid)    202846
 temperature/pet station number..................(Tempid)    202846
 starting year of simulation.................(Start year)      1958
 starting month of simulation...............(Start month)         1
 ending year of simulation.....................(End year)      1990
 ending month of simulation...................(End month)        12
 temperature station latitude.................(Temp lat)     43.03
 Heat index......................................(Hid)       40.00


 ET multiplication factor for each month
 1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
```

DRAINAGE SYSTEM DESIGN
****

*** CONVENTIONAL DRAINAGE ***

JOB TITLE: DR, 20 ft tile spacing, Kilmanagh Soil = KilmanCM, Flint Weather, WET SLOPE = .68, SF = 1.25, PLANT DAYS = 8, 1958-90

```
                     STMAX = 2.50 CM                    SOIL SURFACE
__/)____________________________________________________________/)__
              :                                                    :
              :                                                    :
              :                                                    :
              :                                                    :
              :                                                    :
        ADEPTH =152. CM                              DDRAIN = 102 CM
              :                                                    :
              :                                                    :
              :     O-------------SDRAIN =  610 CM -----------O   -
              :      \                                             :
              : EFFRAD = .51 CM                                    :
              :                                      HDRAIN = 30. CM
              :                                                    :
              :                                                    :
 - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
              :
              :
              :
              :                                    IMPERMEABLE LAYER
____________________________________________________________________
////////////////////////////////////////////////////////////////////
```

DEPTH (CM)	SATURATED HYDRAULIC CONDUCTIVITY (CM/HR)
.0 - 74.0	3.400
74.0 - 112.0	2.790
112.0 - 152.0	.150

depth to drain = 102.0 Cm
effective depth from drain to impermeable layer = 29.8 Cm
distance between drains = 610.0 Cm
maximum depth of surface ponding = 2.50 Cm
effective depth to impermeable layer = 131.8 Cm
drainage coefficient(as limited by subsurface outlet) = .95 Cm/day
actual depth from surface to impermeable layer = 152.0 Cm
surface storage that must be filled before water can move to drain = .50 Cm
factor -g- in kirkham eq. 2-17 =13.01
width of ditch bottom = 1.0 Cm
side slope of ditch (horiz:vert) = .10 : 1.00
Initial water table depth = 38.0 Cm

DEPTH OF WEIR FROM THE SURFACE

DATE	1/ 1	2/ 1	3/ 1	4/ 1	5/ 15	6/ 15
WEIR DEPTH	102.0	102.0	102.0	102.0	102.0	102.0

DATE	7/ 1	8/ 15	9/ 1	10/ 1	11/ 1	12/ 1
WEIR DEPTH	102.0	102.0	102.0	102.0	102.0	102.0

SOIL INPUTS
****

VOID VOLUME (CM)	WATER TABLE DEPTH (CM)
.0	.0
1.0	27.6
2.0	39.3
3.0	49.1
4.0	59.0
5.0	69.5
6.0	80.2
7.0	91.1
8.0	101.4
9.0	111.8
10.0	121.9
11.0	131.1
12.0	140.4
13.0	149.7
14.0	158.2
15.0	166.7
16.0	175.1
17.0	183.6
18.0	192.1
19.0	200.4
20.0	206.9
21.0	213.4
22.0	219.8
23.0	226.3
24.0	232.8
25.0	239.2
26.0	245.7
27.0	252.2
28.0	258.7
29.0	265.1
30.0	271.6
35.0	303.9
40.0	336.3
45.0	368.6
50.0	400.9
60.0	465.6
70.0	567.5
80.0	711.7
90.0	855.8

SOIL WATER CHARACTERISTIC VS VOID VOLUME VS UPFLUX

HEAD (CM)	WATER CONTENT (CM/CM)	VOID VOLUME (CM)	UPFLUX (CM/HR)
.0	.4760	.00	.5000
10.0	.4520	.13	.5000
20.0	.4280	.52	.1599
30.0	.4040	1.17	.0527
40.0	.3800	2.07	.0237
50.0	.3780	3.09	.0131
60.0	.3760	4.10	.0048
70.0	.3742	5.05	.0029
80.0	.3725	5.98	.0017
90.0	.3707	6.90	.0011
100.0	.3690	7.86	.0009
110.0	.3670	8.83	.0007
120.0	.3650	9.80	.0005
130.0	.3629	10.88	.0004
140.0	.3609	11.96	.0004
150.0	.3589	13.03	.0003
160.0	.3569	14.21	.0002
170.0	.3549	15.39	.0002
180.0	.3529	16.57	.0001
190.0	.3508	17.75	.0001
200.0	.3488	18.93	.0000
210.0	.3468	20.48	.0000
220.0	.3448	22.02	.0000
230.0	.3428	23.57	.0000
240.0	.3408	25.12	.0000
250.0	.3387	26.66	.0000
260.0	.3367	28.21	.0000
270.0	.3347	29.75	.0000
280.0	.3327	31.30	.0000
290.0	.3307	32.85	.0000
300.0	.3287	34.39	.0000
350.0	.3213	42.12	.0000
400.0	.3191	49.85	.0000
450.0	.3169	57.58	.0000
500.0	.3147	65.31	.0000
600.0	.3104	72.25	.0000
700.0	.3060	79.19	.0000
800.0	.3017	86.13	.0000
900.0	.2973	93.06	.0000

GREEN AMPT INFILTRATION PARAMETERS

W.T.D. (CM)	A (CM)	B (CM)
.000	.000	3.300
10.000	.440	3.300
20.000	.890	3.300
40.000	1.710	3.300
60.000	1.770	3.270
80.000	1.840	3.270
100.000	1.890	3.270
150.000	4.050	3.270
200.000	4.050	3.270
1000.000	4.050	3.270

TRAFFICABILITY
****

requirements	first period	second period
-minimum air volume in soil (cm):	3.40	3.40
-Maximum allowable daily rainfall(cm):	1.30	1.30
-Minimum time after rain to continue tilling:	2.00	2.00
Working times		
-date to begin counting work days:	4/20	9/ 1
-date to stop counting work days:	6/ 1	11/ 1
-first work hour of the day:	8	8
-last work hour of the day:	20	18

crop
****

soil moisture at crop wilting point = .22

High water stress: begin stress period on 5/ 1
end stress period on 9/ 1
crop is in stress when water table is above 30 cm
drought stress: begin stress period on 5/ 1
end stress period on 9/ 1

MO	DAY	ROOTING DEPTH(CM)
1	1	3.0
5	7	3.0
5	25	5.0
6	8	20.0
6	22	35.0
7	13	40.0
8	9	45.0
9	10	30.0
10	15	10.0
10	20	3.0
12	31	3.0

YIELD INPUTS

```
*************

last planting day without yield loss (JLAST):        130
length of growing season (IGROW)            :        105
1st planting day reduction factor (PDRF)    :   6.000000E-01
days using 1st planting delay fact (DELAY1) :     22.000000
2nd planting day reduction factor (PDRF2)   :      1.800000
total days of work before planting (REQWRK) :      8.000000
IOW:          30
IOH:          11
SI :       11.160000
D  :       -1.170000
E  :    5.800000E-02
FO :   -5.000000E-04
YI :      100.000000
SF :        1.250000
YRMAX :    0.000000E+00
YSLOPE:        1.050000
YRDMAX:      100.000000
DSLOPE:    6.800000E-01
PD :          121
IGR:          105
SDF:            1
IPS(I),IPE(I),CSD(I),I=1,IOH
   0    9       .2000
  10   19       .2000
  20   35       .2200
  36   49       .2800
  50   59       .3200
  60   69       .2800
  70   79       .1900
  80   89       .1200
  90   99       .0800
 100  104       .0400
 105  105       .0200
CSI(I),I=1,IOW
          .0000        .0000        .0000        .0000        .0000
          .0000        .5000        .5000       1.0000       1.0000
         1.0000       1.0000       1.7500       2.0000       2.0000
         1.3000       1.3000       1.3000       1.3000       1.3000
         1.2000       1.0000        .5000        .0000        .0000
          .0000        .0000        .0000        .0000        .0000


**> Total simulation time=   4.333 minutes.
```

```
========================================================================
dr2k12.lis
========================================================================
C:\DM40\INPUT40\DR2K12.GEN
C:\DM40\INPUT40\KILCMK12.SIN
C:\DM40\INPUT40\CN105K12.YIN
========================================================================
dr2k12.gen
========================================================================
*** Job Title ***
DR, 20 ft tile spacing, Kilmanagh Soil = KilmanCM, Flint Weather, dry
slope 1.0
WET SLOPE = .68, SF = 1.25, PLANT DAYS = 8, 1958-90
*** Printout and Input Control ***
 3 1 0 C:\DM40\OUTPUT40\
*** Climate ***
202846   C:\DM40\WEATHER\FNT5891.RAI
202846   C:\DM40\WEATHER\FNT5890.TEM
1958  1 1990 12 4303  40
 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
*** Drainage System Design ***
 1
    102.00     29.84    610.00      2.50      0.95      0.50     13.01
 38.00
 0 ,  0 ,  0
 0 ,  0 ,  0 ,  0
 0 ,  0 ,  0 ,  0 ,  0
      1.00      0.10
 1107 1107 1107 110715 7615 51 1 5115 76 1107 1107 1107 1107
*** Soils ***
    152.00      0.51
  74. 3.40 112. 2.79 152. 0.15
99
*** Trafficability ***
 420 6 1 820              3.4       1.3       2.0
 9 111 1 818              3.4       1.3       2.0
*** Crop ***
 0.220
 5 1 9 1       30.00
 5 1 9 1
11
 1 1  3.0  5 7  3.0  525  5.0  6 8 20.0  622 35.0  713 40.0  8 9 45.0
910 30.0
1015 10.0 1020  3.0 1231  3.0
*** Wastewater Irrigation ***
 0   0 0 365  0  0
 0 0      0 0      0 0      0 0
   0.00000   0.00000 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.00 0.00
========================================================================
cn105k12.yin
========================================================================
  130  105   0.6000   8.0000   1.8000   22.0000
3011        11.1600   -1.1700   0.0580   -0.0005  100.0000    1.2500
 100.000   1.050 100.000   0.680 121 105   1
  0  90.20 10 190.20 20 350.22 36 490.28 50 590.32 60 690.28 70 790.19
80 890.12
 90 990.081001040.041051050.02
0.000.000.000.000.000.000.500.501.001.001.001.001.752.002.001.301.301.30
1.301.30
1.201.000.500.000.000.000.000.000.000.00
```

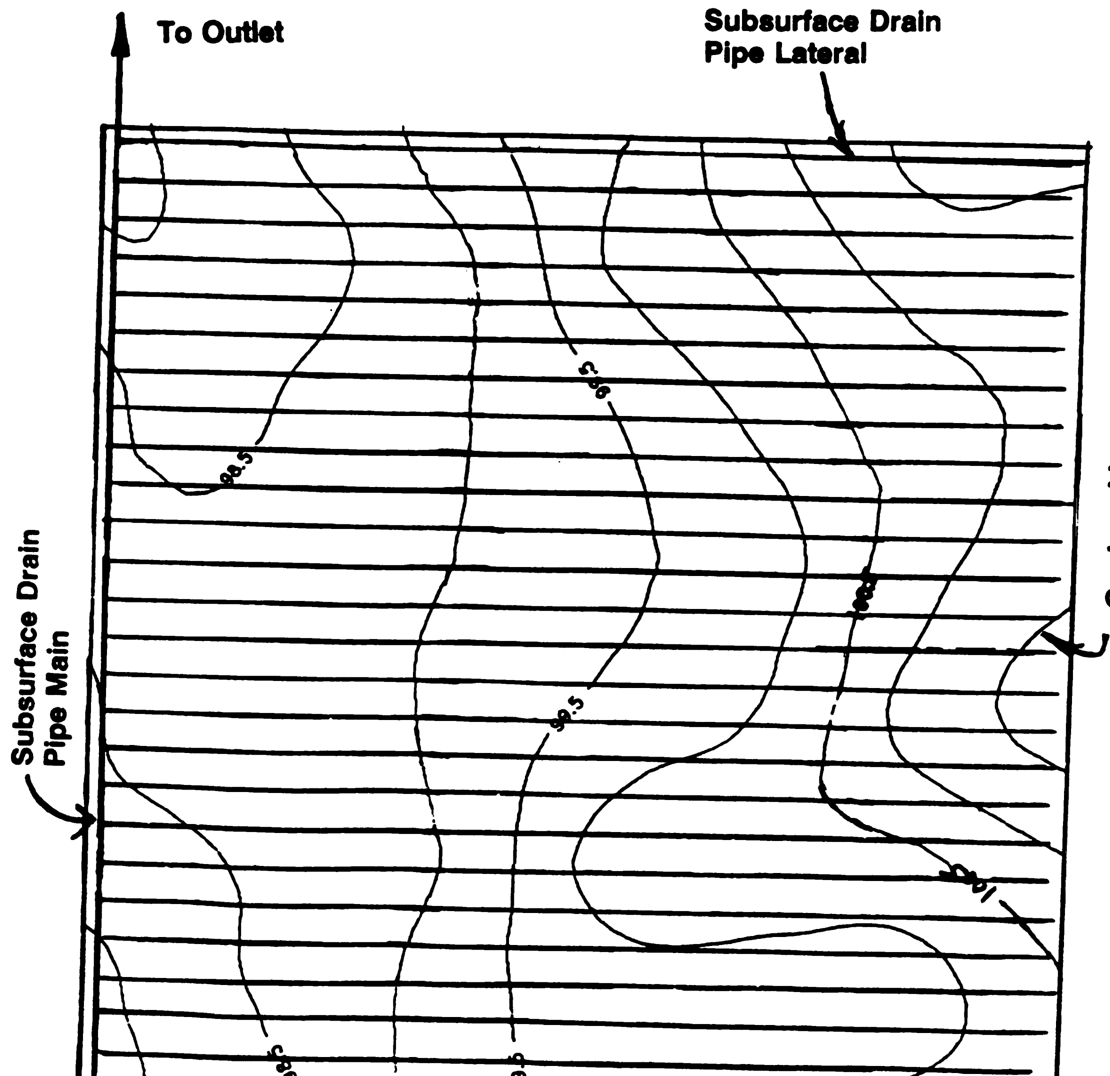
```
==========================================================================
kilcmk12.sin
==========================================================================
4 LAYER- KILMANAGH, HURON CO. MICHIGAN

1120
   0.47600       0.0
   0.38000     -40.0
   0.37600     -60.0
   0.36900    -100.0
   0.32200    -333.0
   0.29300   -1000.0
   0.26600   -2000.0
   0.25700   -3000.0
   0.24800   -5000.0
   0.24100  -10000.0
   0.23700  -15000.0
    0.0000    0.0000    0.5000
    3.0000    0.0120    0.5000
    6.0000    0.0470    0.5000
    9.0000    0.1050    0.5000
   12.0000    0.1870    0.5000
   15.0000    0.2930    0.3417
   20.0000    0.5200    0.1599
   25.0000    0.8130    0.0869
   30.0000    1.1700    0.0527
   35.0000    1.5910    0.0340
   40.0000    2.0720    0.0237
   45.0000    2.5820    0.0172
   60.0000    4.1020    0.0048
   75.0000    5.5200    0.0020
   90.0000    6.8960    0.0011
  120.0000    9.7970    0.0005
  150.0000   13.0340    0.0003
  200.0000   18.9320    0.0000
  500.0000   65.3140    0.0000
 1000.0000  100.0000    0.0000
10
      0.00      0.00      3.30
     10.00      0.44      3.30
     20.00      0.89      3.30
     40.00      1.71      3.30
     60.00      1.77      3.27
     80.00      1.84      3.27
    100.00      1.89      3.27
    150.00      4.05      3.27
    200.00      4.05      3.27
   1000.00      4.05      3.27
 0
 0
```

APPENDIX C

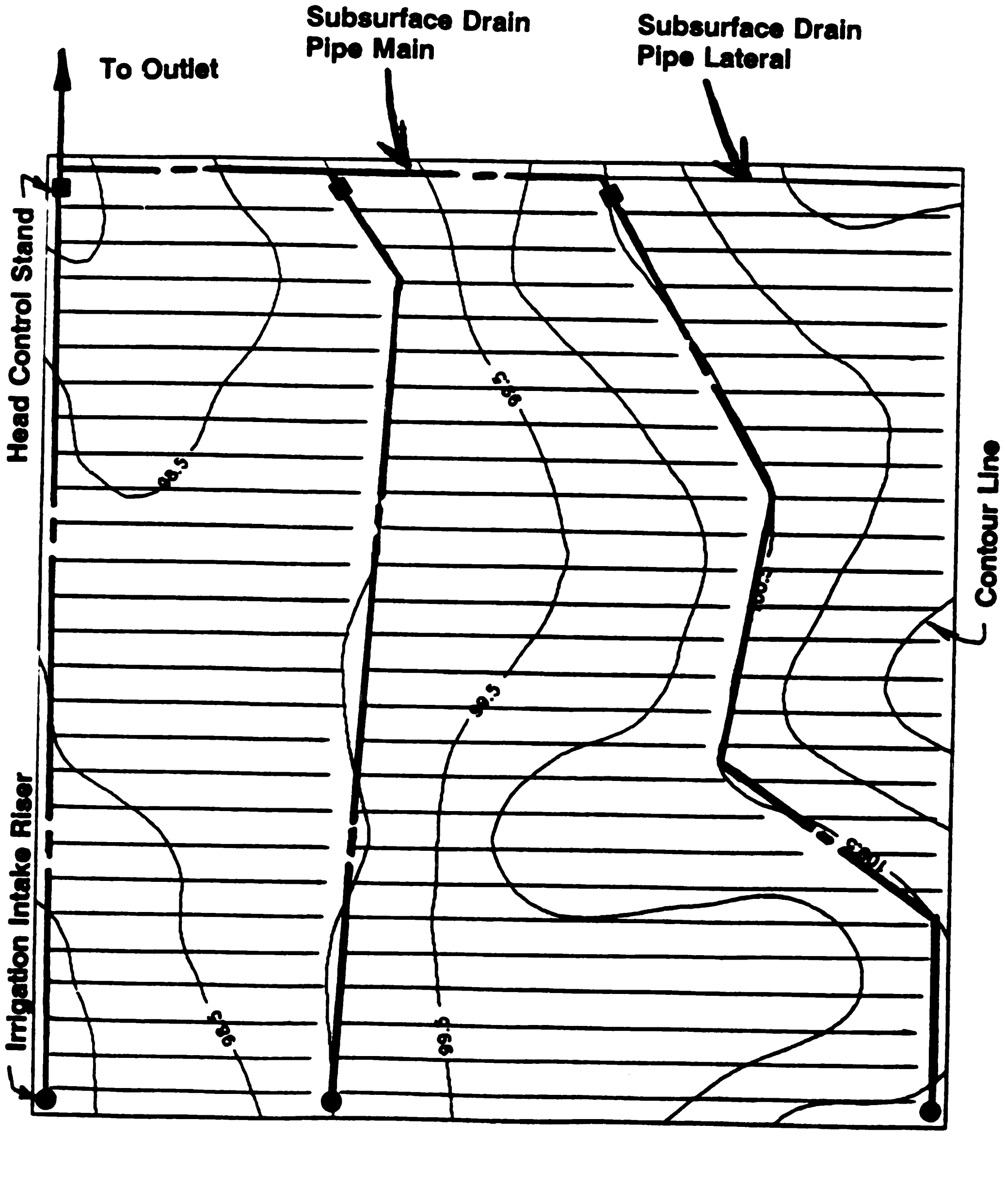
DRAINAGE-ONLY SITE DESIGN

by Dr. Harold Belcher
Department of Agricultural Engineering
Michigan State University



APPENDIX D

SUBIRRIGATION SITE DESIGN
by Dr. Harold Belcher
Department of Agricultural Engineering
Michigan State University



APPENDIX E

AVERAGE MONTHLY TEMPERATURE AND PRECIPITATION FOR BAD AXE, HARBOR BEACH, AND FLINT, MICHIGAN FOR THE PERIOD 1951-1980

Station	Temperature (°F)			Precipitation (in)
Bad Axe	Avg Daily Max	Avg Daily Min	Average	Average
January	29.1	14.3	21.7	1.86
February	31.2	14.3	22.7	1.87
March	39.5	22.2	30.9	2.30
April	55.0	33.8	44.4	2.66
May	67.0	43.0	55.0	2.60
June	77.4	53.5	65.4	2.86
July	81.5	57.5	69.5	3.01
August	80.2	56.4	68.3	2.66
September	72.3	49.9	61.1	2.48
October	62.0	41.3	51.7	2.39
November	45.8	31.0	38.4	2.39
December	33.4	20.3	26.9	2.09
Yearly Avg	56.2	36.5	46.3	29.17
Harbor Beach	Avg Daily Max	Avg Daily Min	Average	Average
January	28.7	15.3	22.0	2.66
February	30.5	15.8	23.2	2.31
March	37.7	23.2	30.5	2.47
April	52.0	34.1	43.0	2.84
May	63.0	42.7	52.8	2.63
June	73.9	53.2	63.5	3.18
July	78.2	58.7	68.5	3.22
August	77.3	58.4	67.9	3.16
September	70.3	51.9	61.1	2.75
October	60.2	42.8	51.5	2.66
November	45.4	32.2	38.8	2.89
December	33.3	21.3	27.3	3.17
Yearly Avg	54.2	37.5	45.8	33.84
Flint	Avg Daily Max	Avg Daily Min	Average	Average
January	31.9	17.1	24.5	1.63
February	32.8	16.7	24.8	1.76
March	41.3	24.1	32.7	2.20
April	55.9	34.7	45.3	2.85
May	68.0	44.7	56.4	3.16
June	78.5	54.7	66.6	3.32
July	83.5	58.9	71.2	2.86
August	81.6	57.6	69.6	3.43
September	73.4	50.5	62.0	2.53
October	62.1	40.6	51.4	2.09
November	46.3	30.1	38.2	2.05
December	34.6	20.6	27.2	1.70
Yearly Avg	57.5	37.5	47.5	29.58

APPENDIX F

DRAINMOD WATER BALANCE VERIFICATION

Dr. Harold Belcher
Department of Agricultural Engineering
Michigan State University

Introduction:

DRAINMOD simulation results have been compared to observed data at a number of locations including North Carolina, South Carolina, Louisiana, Florida, Georgia, Iowa, and Ohio [note: references are probably in DRAINMOD USER MANUAL]. In all cases, it was reported the simulated water balance results (water table depth and/or subdrain discharge) were reasonably close to observed data. To evaluate applicability of the model to Michigan climate and poorly drained soils, observed water table depth data from a water table management research site near Bannister Michigan was compared to Drainmod simulated water table depths for two years of record.

Bannister Site:

The Bannister site is described by Belcher, 1990. Soil at the site is classified as a Ziegenfuss silty clay loam and has particle size gradation and hydraulic properties similar to typical Saginaw Bay area shallow water table, poorly drained soils (see Table 1).

Soil property inputs for DRAINMOD resulted from application of the DRAINMOD "soilprep" computer model using the field measured soil water characteristic data as follows:

Lateral saturated hydraulic conductivity values for each soil layer used for DRAINMOD (see Table 1) are the mean of the field determined values reported by Fogiel and Belcher (1990) for the areas that do not include sand. The values used are the average of velocity permeameter (Merva, 1987) lateral measurements, 36 each at depths 0.45 m, 0.60 m and 0.75 m. For the "soilprep" model, the lateral conductivities were reduced by 50% to approximate vertical saturated hydraulic conductivity for each layer.

Results:

The results of this study are presented in Figures 1, 2 and 3 for the 1986 growing season and subdrain lateral spacings of 6 m, 12 m and 18 m, respectively and Figures 4, and 5 for the 1987 growing season and 6 m and 18 m subdrain lateral spacings. The reader is referred to Belcher, 1990 for a detailed description of the Bannister site, instrumentation and observed water table figures.

Table 2. Properties of a Ziegenfuss soil, typical at the Bannister, Michigan research site (Rosek, 1992).

Sample	Depth	Sand	Clay	Silt	Organic Matter	Bulk Density	Lat. Sat. K
	inches	%	%	%	%	g/cm^3	cm/hr
B-1 Ap	0-9	24	38	38	3.2	1.29	3.0*
B-1 Bg1	9-25	18	36	46	1.2	1.52	0.8
B-1 Bg2	25-38	28	36	36	0.7	1.50	1.1
B-1 C1	38-52	20	36	44	0.7	1.56	1.1
B-1 C2	52-60	0	37	63	0.7	1.71	0.1*

* Values assumed for DRAINMOD simulations.

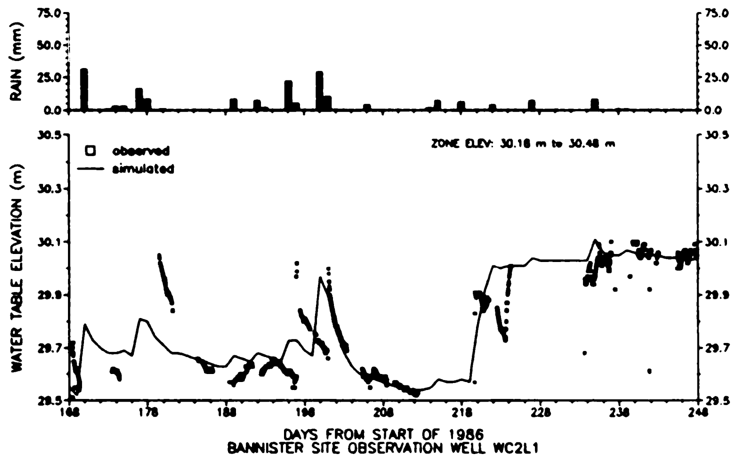


Figure 1. Observed and predicted water table elevation (m) for subdrains spaced at 2 m for 1986 growing season at the Bannister site.

Table 3. Volumetric water contents (cm/cm) at various soil tensions (cm) for typical Ziegenfuss soil at Bannister, Michigan research site (Rosek, 1992).

Sample	0 cm	40 cm	60 cm	100 cm	333 cm	1000 cm
B-1 Ap	0.5241	0.4646	0.4604	0.4567	0.442	0.4304
B-1 Bg1	0.5011	0.4343	0.4299	0.4258	0.3981	0.388
B-1 Bg2	0.5151	0.4486	0.4451	0.4362	0.388	0.3816
B-1 C1	0.5212	0.4541	0.4492	0.4318	0.3906	0.3786
B-1 C2	0.5647	0.5013	0.4972	0.4906	0.4483	0.4334

Sample	2000 cm	3000 cm	5000 cm	10000 cm	15000 cm	
B-1 Ap	0.415	0.4074	0.3864	0.3805	0.368	
B-1 Bg1	0.3769	0.3698	0.3649	0.3589	0.3475	
B-1 Bg2	0.3686	0.3606	0.3469	0.3412	0.3305	
B-1 C1	0.3608	0.3527	0.3415	0.3361	0.3269	
B-1 C2	0.4154	0.4052	0.3855	0.3802	0.3688	

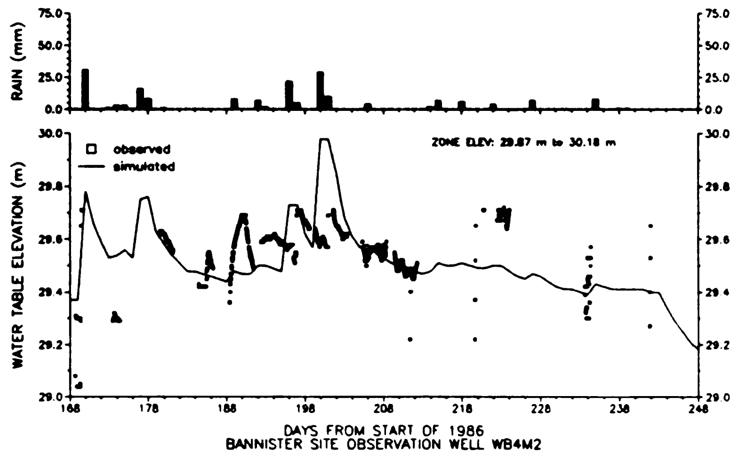


Figure 2. Observed and predicted water table elevation (m) for subdrains spaced at 12 m for 1986 growing season at the Bannister site.

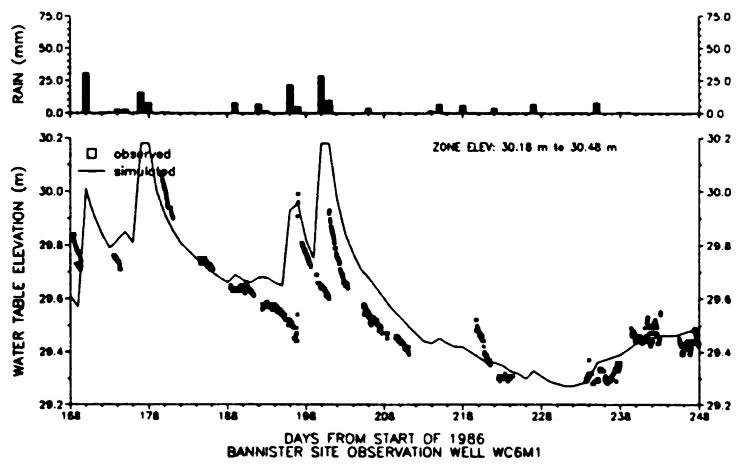


Figure 3. Observed and predicted water table elevation (m) for subdrains spaced at 18 m for 1986 growing season at the Bannister site.

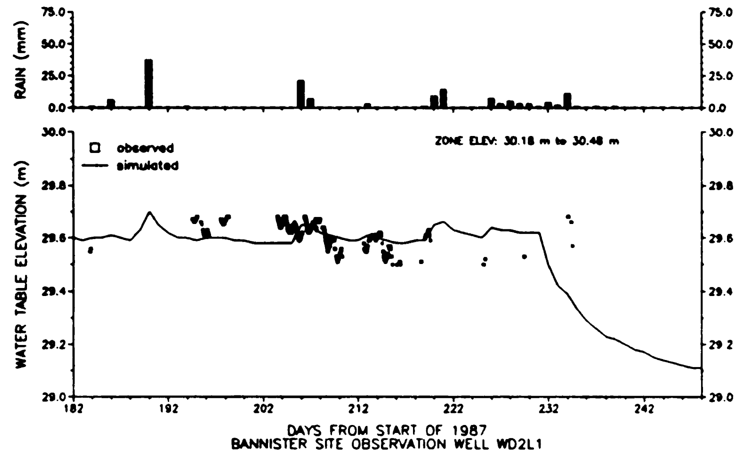


Figure 4. Observed and predicted water table elevation (m) for subdrains spaced at 6 m for 1987 growing season at the Bannister site.

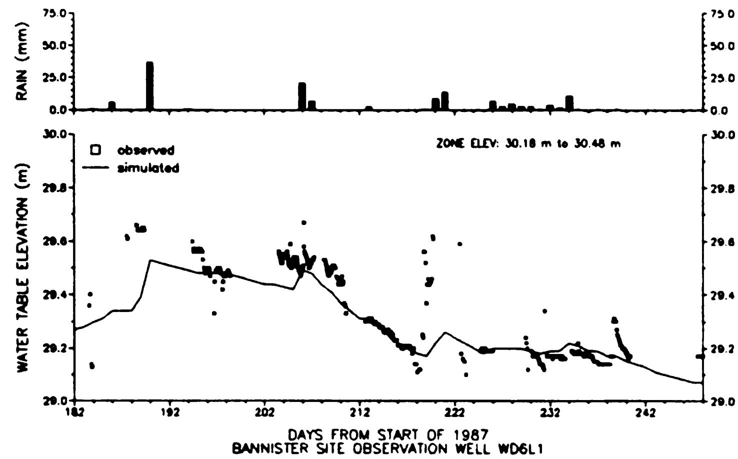


Figure 5. Observed and predicted water table elevation (m) for subdrains spaced at 16 m for 1987 growing season at the Bannister site.

Discussion:

The predicted water table elevations in Figures 1 through 5 result from DRAINMOD version 4.0 without modification of inputs to calibrate the model.

DRAINMOD allows a single water table control weir setting per month. During both the 1986 and 1987 seasons, the Bannister water table control weirs were lowered following selected rainfall events thus weir settings were sometimes altered more often than one time in a month. When this occurred, a variance between observed and predicted water table depth is to be expected. This is best illustrated by looking at Figure 2 at 188 days.

The water table at the Bannister site was observed by monitoring instrumentation that allowed hourly observation. During peak evapotranspiration days, it was observed that the water table varied as much as 15 cm from morning to mid-afternoon. DRAINMOD provides a daily water table depth output which does not provide the observed hourly fluctuation.

The water table depth instrumentation at Bannister has a limited operating range. Examination of the figures indicate that the actual water table depth sometimes exceeded the upper limits. Thus, DRAINMOD data showing a higher water table elevation than was observed are not unexpected.

Considering the preceding discussion, the results as provided by Figures 1 through 4 indicate strongly that DRAINMOD does accurately model the change in water table depth with time for a poorly drained soil in Michigan.

References:

Belcher, H. W. 1990. Water table management to maximize the economic efficiency of biomass production. PhD. Dissertation. Agricultural Engineering Department, Michigan State University.

Fogiel, A. C. and H. W. Belcher. 1990. Watertable management effects on soil structure. ASAE Paper No. 90-2604. ASAE, St. Joseph, MI.

Rossek, M. 1992. Personal Communication, Michigan State University, E. Lansing, MI.

Merva, G. E. 1987. The velocity permeameter technique for rapid determination of hydraulic conductivity in-situ. Proceedings of the Third International Workshop on Land Drainage. Ohio State University, Columbus, OH.

APPENDIX G

INVESTMENT COSTS

Contractor Estimates For Investment Options

DR20
Cost Estimates for Modifying a Conventional Drainage System from 60-ft Tile Spacings to 20-ft Spacings

Item of Work	Diameter (inches)	Quantity (# or ft)	Item Cost	Item Cost	Item Cost	Avg Cost
Laterals	4	58660	$20,444	$22,984	$19,758	$21,062
			$20,444	$22,984	$19,758	$21,062

DR30
Cost Estimates for Modifying a Conventional Drainage System from 60-ft Tile Spacings to 30-ft Spacings

Item of Work	Diameter (inches)	Quantity (# or ft)	Item Cost	Item Cost	Item Cost	Avg Cost
Laterals	4	29330	$10,472	$11,692	$10,079	$10,748
			$10,472	$11,692	$10,079	$10,748

DR60
Existing System: No Costs

SI20S or SI20W
Cost Estimates for Modifying a Conventional Drainage System from 60-ft Tile Spacings to 20-ft Spacings and Retrofitting for Subirrigation, Surface Water Source or Well Water Source

Item of Work	Diameter (inches)	Quantity (# or ft)	Item Cost	Item Cost	Item Cost	Avg Cost
Head Stands		3	$1,900	$2,600	$1,135	$1,878
Irrigation Inlets		3	$400	$400	$250	$350
Water Supply	6	1100	$4,120	$2,190	$3,961	$3,424
Laterals	4	58660	$19,994	$22,371	$19,392	$20,586
Mains/Submain	6	1027	$1,180	$1,199	$1,174	$1,184
(2)	8	1405	$2,158	$2,173	$2,394	$2,242
(3)	10	856	$2,190	$2,040	$2,456	$2,229
(4)	12	370	$1,197	$1,149	$1,396	$1,247
			$33,139	$34,123	$32,158	$33,140

SI30S or SI30W
Cost Estimates for Modifying a Conventional Drainage System from 60-ft Tile Spacings to 30-ft Spacings and Retrofitting for Subirrigation, Surface Water Source or Well Water Source

Item of Work	Diameter (inches)	Quantity (# or ft)	Item Cost	Item Cost	Item Cost	Avg Cost
Head Stands		3	$1,900	$2,600	$1,135	$1,878
Irrigation Inlets		3	$400	$400	$250	$350
Water Supply	6	1100	$4,120	$2,190	$3,961	$3,424
Laterals	4	29330	$10,022	$11,225	$9,713	$10,320
Mains/Submain	6	1027	$1,180	$1,199	$1,174	$1,184
(2)	8	1405	$2,158	$2,173	$2,394	$2,242
(3)	10	856	$2,190	$2,040	$2,456	$2,229
(4)	12	370	$1,197	$1,149	$1,396	$1,247
			$23,166	$22,978	$22,479	$22,875

SI60S or SI60W
Cost Estimates for Retrofitting a Conventional Drainage System at 60-ft Tile Spacings to a Subirrigation System at 60-ft Tile Spacings, Surface Water Source or Well Water Source

Item of Work	Diameter (inches)	Quantity (# or ft)	Item Cost	Item Cost	Item Cost	Avg Cost
Head Stands		3	$1,900	$2,600	$1,135	$1,878
Irrigation Inlets		3	$400	$400	$250	$350
Water Supply	6	1100	$4,130	$2,350	$3,967	$3,482
Mains/Submain	6	1027	$1,190	$1,272	$1,180	$1,214
(2)	8	1405	$2,168	$2,288	$2,400	$2,285
(3)	10	856	$2,200	$2,180	$2,462	$2,281
(4)	12	370	$1,207	$1,261	$1,402	$1,290
			$13,194	$12,351	$12,796	$12,781

SUMMARY OF COSTS FOR EACH INVESTMENT OPTION

	DR20	DR30	DR60	SI20S	SI30S	SI60S	SI20W	SI30W	SI60W
Well	$0	$0	$0	$0	$0	$0	$15,000	$15,000	$15,000
Pump	$0	$0	$0	$4,600	$4,600	$4,600	$5,400	$5,400	$5,400
CS	$0	$0	$0	$2,228	$2,228	$2,228	$2,228	$2,228	$2,228
Tile	$21,062	$10,748	$0	$30,912	$20,646	$10,552	$30,912	$20,646	$10,552
TOTAL:	$21,062	$10,748	$0	$37,740	$27,475	$17,381	$53,540	$43,275	$33,181

DEPRECIATION FOR EACH COMPONENT

	DR20	DR30	DR60	SI20S	SI30S	SI60S	SI20W	SI30W	SI60W
Well	$0	$0	$0	$0	$0	$0	$1,000	$1,000	$1,000
Pump	$0	$0	$0	$657	$657	$657	$771	$771	$771
CS	$0	$0	$0	$149	$149	$149	$149	$149	$149
Tile	$1,404	$717	$0	$2,061	$1,376	$703	$2,061	$1,376	$703
TOTAL:	$1,404	$717	$0	$2,866	$2,182	$1,509	$3,981	$3,296	$2,623

OPERATING COSTS FOR DIFFERENT COMPONENTS

	DR20	DR30	DR60	SI20S	SI30S	SI60S	SI20W	SI30W	SI60W
Well	$0	$0	$0	$0	$0	$0	$0	$0	$0
Pump	$0	$0	$0	$33	$33	$33	$39	$39	$39
CS	$0	$0	$0	$1	$1	$1	$1	$1	$1
Tile	$0	$0	$0	$0	$0	$0	$0	$0	$0
TOTAL:	$0	$0	$0	$34	$34	$34	$40	$40	$40

SUMMARY OF COSTS FOR EACH INVESTMENT OPTION IN PER ACRE TERMS

	DR20	DR30	DR60	SI20S	SI30S	SI60S	SI20W	SI30W	SI60W
Well	$0	$0	$0	$0	$0	$0	$375	$375	$375
Pump	$0	$0	$0	$115	$115	$115	$135	$135	$135
CS	$0	$0	$0	$56	$56	$56	$56	$56	$56
Tile	$527	$269	$0	$773	$516	$264	$773	$516	$264
TOTAL:	$527	$269	$0	$944	$687	$435	$1,339	$1,082	$830

DEPRECIATION FOR EACH COMPONENT IN PER ACRE TERMS

	DR20	DR30	DR60	SI20S	SI30S	SI60S	SI20W	SI30W	SI60W
Well	$0	$0	$0	$0	$0	$0	$25	$25	$25
Pump	$0	$0	$0	$16	$16	$16	$19	$19	$19
CS	$0	$0	$0	$4	$4	$4	$4	$4	$4
Tile	$35	$18	$0	$52	$34	$18	$52	$34	$18
TOTAL:	$35	$18	$0	$72	$55	$38	$100	$82	$66

OPERATING COSTS FOR DIFFERENT COMPONENTS IN PER ACRE TERMS

	DR20	DR30	DR60	SI20S	SI30S	SI60S	SI20W	SI30W	SI60W
Well	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Pump	$0.00	$0.00	$0.00	$0.82	$0.82	$0.82	$0.96	$0.96	$0.96
CS	$0.00	$0.00	$0.00	$0.04	$0.04	$0.04	$0.04	$0.04	$0.04
Tile	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
TOTAL:	$0.00	$0.00	$0.00	$0.86	$0.86	$0.86	$1.00	$1.00	$1.00

APPENDIX H

SIMULATION YIELD RESULTS

H1: DR20 - Drainage Only at 20-Ft Tile Spacings

****

----------RUN STATISTICS ---------- time: 1/ 7/1993 @ 0:25

input file: C:\DM40\INPUT40\DR2K12.LIS

parameters: free drainage and yields calculated

drain spacing = 610. cm drain depth = 102.0 cm

	SDI - STRESS		plant	plant	harv.	RELATIVE YIELDS (%)			
	excess	drought	date	delay	date	excess	drought	delay	overall
1958	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1959	.0	22.9	125	0.	230	100.0	75.9	100.0	75.9
1960	.0	15.3	125	0.	230	100.0	84.0	100.0	84.0
1961	.0	3.0	125	0.	230	100.0	96.8	100.0	96.8
1962	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1963	.0	45.0	125	0.	230	100.0	52.8	100.0	52.8
1964	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1965	.0	28.9	125	0.	230	100.0	69.7	100.0	69.7
1966	.0	6.1	125	0.	230	100.0	93.6	100.0	93.6
1967	.0	.4	125	0.	230	100.0	99.6	100.0	99.6
1968	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1969	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1970	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1971	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1972	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1973	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1974	.1	25.0	125	0.	230	100.0	73.8	100.0	73.8
1975	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1976	.0	.4	125	0.	230	100.0	99.6	100.0	99.6
1977	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1978	.0	38.0	125	0.	230	100.0	60.1	100.0	60.1
1979	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1980	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1981	.0	.3	125	0.	230	100.0	99.7	100.0	99.7
1982	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1983	.0	1.4	125	0.	230	100.0	98.6	100.0	98.6
1984	.0	12.5	125	0.	230	100.0	86.8	100.0	86.8
1985	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1986	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1987	.0	33.3	125	0.	230	100.0	65.0	100.0	65.0
1988	.0	38.3	125	0.	230	100.0	59.8	100.0	59.8
1989	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1990	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
AVG	.0	8.2	125.	0.	230.	100.0	91.4	100.0	91.4

H2: DR30 - Drainage Only at 30-Ft Tile Spacings

```
*********************************************************************************
----------RUN STATISTICS ----------          time:  1/ 7/1993 @  0:29
 input file:   C:\DM40\INPUT40\DR3K12.LIS
 parameters:     free drainage           and yields calculated
                drain spacing =     914. cm   drain depth =  102.0 cm
---------------------------------------------------------------------------------
```

	SDI - STRESS excess	SDI - STRESS drought	plant date	plant delay	harv. date	RELATIVE YIELDS (%) excess	drought	delay	overall
1958	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1959	.0	22.2	125	0.	230	100.0	76.7	100.0	76.7
1960	.0	14.8	125	0.	230	100.0	84.5	100.0	84.5
1961	.0	2.9	125	0.	230	100.0	97.0	100.0	97.0
1962	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1963	.0	44.8	125	0.	230	100.0	52.9	100.0	52.9
1964	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1965	.0	28.5	125	0.	230	100.0	70.1	100.0	70.1
1966	.0	5.7	125	0.	230	100.0	94.0	100.0	94.0
1967	.0	.4	125	0.	230	100.0	99.6	100.0	99.6
1968	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1969	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1970	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1971	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1972	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1973	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1974	2.2	23.7	125	0.	230	98.5	75.1	100.0	74.0
1975	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1976	.0	.4	125	0.	230	100.0	99.6	100.0	99.6
1977	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1978	.0	37.6	125	0.	230	100.0	60.5	100.0	60.5
1979	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1980	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1981	.0	.2	125	0.	230	100.0	99.8	100.0	99.8
1982	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1983	.0	1.2	125	0.	230	100.0	98.8	100.0	98.8
1984	.0	12.3	125	0.	230	100.0	87.1	100.0	87.1
1985	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1986	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1987	.0	33.1	125	0.	230	100.0	65.2	100.0	65.2
1988	.0	38.2	125	0.	230	100.0	59.9	100.0	59.9
1989	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1990	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
AVG	.1	8.1	125.	0.	230.	100.0	91.5	100.0	91.5

H3: DR60 - Drainage Only at 60-Ft Tile Spacings

```
********************************************************************************
----------RUN STATISTICS ----------          time:  1/ 7/1993  @  0:20
input file:   C:\DM40\INPUT40\DR6K12.LIS
parameters:    free drainage           and yields calculated
               drain spacing =    1830. cm   drain depth =  102.0 cm
--------------------------------------------------------------------------------
```

	SDI - STRESS excess	SDI - STRESS drought	plant date	plant delay	harv. date	RELATIVE YIELDS (%) excess	RELATIVE YIELDS (%) drought	RELATIVE YIELDS (%) delay	RELATIVE YIELDS (%) overall
1958	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1959	.0	17.0	125	0.	230	100.0	82.2	100.0	82.2
1960	.0	13.0	125	0.	230	100.0	86.3	100.0	86.3
1961	.0	2.0	126	0.	231	100.0	97.9	100.0	97.9
1962	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1963	.0	42.3	125	0.	230	100.0	55.6	100.0	55.6
1964	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1965	.0	26.3	125	0.	230	100.0	72.4	100.0	72.4
1966	.0	4.5	125	0.	230	100.0	95.3	100.0	95.3
1967	.0	.4	125	0.	230	100.0	99.6	100.0	99.6
1968	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1969	6.0	.0	125	0.	230	95.9	100.0	100.0	95.9
1970	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1971	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1972	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1973	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1974	13.1	15.7	125	0.	230	91.1	83.5	100.0	76.1
1975	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1976	3.0	.0	125	0.	230	98.0	100.0	100.0	98.0
1977	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1978	.0	35.2	125	0.	230	100.0	63.1	100.0	63.1
1979	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1980	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1981	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1982	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1983	.0	.0	125	0.	230	100.0	99.9	100.0	99.9
1984	.0	9.3	125	0.	230	100.0	90.2	100.0	90.2
1985	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1986	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1987	.0	31.2	125	0.	230	100.0	67.2	100.0	67.2
1988	.0	36.6	125	0.	230	100.0	61.5	100.0	61.5
1989	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1990	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
AVG	.7	7.1	125.	0.	230.	99.5	92.6	100.0	92.2

H4: SI20 - Subirrigation at 20-Ft Tile Spacings

****

----------RUN STATISTICS ---------- time: 1/ 7/1993 @ 0:34

input file: C:\DM40\INPUT40\SI2K12.LIS

parameters: subirrigation run and yields calculated

drain spacing = 610. cm drain depth = 102.0 cm

	SDI - STRESS excess	drought	plant date	plant delay	harv. date	RELATIVE YIELDS (%) excess	drought	delay	overall
1958	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1959	9.1	.0	125	0.	230	93.8	100.0	100.0	93.8
1960	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1961	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1962	.1	.0	125	0.	230	99.9	100.0	100.0	99.9
1963	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1964	1.4	.0	125	0.	230	99.1	100.0	100.0	99.1
1965	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1966	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1967	2.9	.0	125	0.	230	98.0	100.0	100.0	98.0
1968	26.5	.0	125	0.	230	82.0	100.0	100.0	82.0
1969	11.5	.0	125	0.	230	92.2	100.0	100.0	92.2
1970	7.4	.0	125	0.	230	95.0	100.0	100.0	95.0
1971	.1	.0	125	0.	230	99.9	100.0	100.0	99.9
1972	12.5	.0	125	0.	230	91.5	100.0	100.0	91.5
1973	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1974	1.4	.0	125	0.	230	99.0	100.0	100.0	99.0
1975	3.7	.0	125	0.	230	97.5	100.0	100.0	97.5
1976	21.2	.0	125	0.	230	85.6	100.0	100.0	85.6
1977	.1	.0	125	0.	230	99.9	100.0	100.0	99.9
1978	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1979	12.6	.0	125	0.	230	91.5	100.0	100.0	91.5
1980	10.7	.0	125	0.	230	92.7	100.0	100.0	92.7
1981	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1982	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1983	2.9	.0	125	0.	230	98.0	100.0	100.0	98.0
1984	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1985	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1986	.1	.0	125	0.	230	100.0	100.0	100.0	100.0
1987	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1988	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1989	.5	.0	125	0.	230	99.7	100.0	100.0	99.7
1990	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
AVG	3.8	.0	125.	0.	230.	97.4	100.0	100.0	97.4

H5: SI30 - Subirrigation at 30-Ft Tile Spacings

```
*******************************************************************************
----------RUN STATISTICS ----------              time:  1/ 7/1993 @  0:43
 input file:    C:\DM40\INPUT40\SI3K12.LIS
 parameters:     subirrigation run        and yields calculated
                drain spacing =     914. cm   drain depth =  102.0 cm
-------------------------------------------------------------------------------
```

	SDI - STRESS excess	drought	plant date	plant delay	harv. date	RELATIVE YIELDS (%) excess	drought	delay	overall
1958	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1959	5.9	.0	125	0.	230	96.0	100.0	100.0	96.0
1960	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1961	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1962	.5	.0	125	0.	230	99.7	100.0	100.0	99.7
1963	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1964	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1965	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1966	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1967	1.7	.1	125	0.	230	98.8	99.9	100.0	98.8
1968	11.9	.0	125	0.	230	91.9	100.0	100.0	91.9
1969	8.3	.0	125	0.	230	94.3	100.0	100.0	94.3
1970	7.3	.0	125	0.	230	95.0	100.0	100.0	95.0
1971	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1972	10.2	.0	125	0.	230	93.1	100.0	100.0	93.1
1973	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1974	4.9	.0	125	0.	230	96.7	100.0	100.0	96.7
1975	.2	.0	125	0.	230	99.9	100.0	100.0	99.9
1976	2.6	.0	125	0.	230	98.2	100.0	100.0	98.2
1977	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1978	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1979	.7	.0	125	0.	230	99.5	100.0	100.0	99.5
1980	3.4	.0	125	0.	230	97.7	100.0	100.0	97.7
1981	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1982	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1983	.7	.0	125	0.	230	99.6	100.0	100.0	99.6
1984	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1985	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1986	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1987	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1988	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1989	.4	.0	125	0.	230	99.7	100.0	100.0	99.7
1990	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
AVG	1.8	.0	125.	0.	230.	98.8	100.0	100.0	98.8

H6: SI60 - Subirrigation at 60-Ft Tile Spacings

```
*********************************************************************************
----------RUN STATISTICS ----------          time:  1/ 7/1993  @  0:38
 input file:    C:\DM40\INPUT40\SI6K12.LIS
 parameters:     subirrigation run      and yields calculated
                drain spacing =    1830. cm   drain depth =  102.0 cm
--------------------------------------------------------------------------------
```

	SDI - STRESS excess	SDI - STRESS drought	plant date	plant delay	harv. date	RELATIVE YIELDS (%) excess	RELATIVE YIELDS (%) drought	RELATIVE YIELDS (%) delay	RELATIVE YIELDS (%) overall
1958	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1959	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1960	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1961	.0	.0	126	0.	231	100.0	100.0	100.0	100.0
1962	.5	.0	125	0.	230	99.7	100.0	100.0	99.7
1963	.0	13.2	125	0.	230	100.0	86.1	100.0	86.1
1964	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1965	.0	3.0	125	0.	230	100.0	96.9	100.0	96.9
1966	.0	3.0	125	0.	230	100.0	96.8	100.0	96.8
1967	.0	.3	125	0.	230	100.0	99.7	100.0	99.7
1968	3.7	.0	125	0.	230	97.5	100.0	100.0	97.5
1969	6.0	.0	125	0.	230	95.9	100.0	100.0	95.9
1970	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1971	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1972	.3	.0	125	0.	230	99.8	100.0	100.0	99.8
1973	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1974	14.4	.0	125	0.	230	90.2	100.0	100.0	90.2
1975	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1976	3.0	.0	125	0.	230	98.0	100.0	100.0	98.0
1977	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1978	.0	5.0	125	0.	230	100.0	94.8	100.0	94.8
1979	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1980	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1981	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1982	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1983	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1984	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1985	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1986	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1987	.0	29.9	125	0.	230	100.0	68.6	100.0	68.6
1988	.0	33.4	125	0.	230	100.0	64.9	100.0	64.9
1989	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
1990	.0	.0	125	0.	230	100.0	100.0	100.0	100.0
AVG	.8	2.7	125.	0.	230.	99.4	97.2	100.0	96.6

APPENDIX I

SIMULATION WATER BALANCE RESULTS

I1: DR20 - Drainage Only at 20-Ft Tile Spacings

```
********************************************************************************
----------RUN STATISTICS ----------          time:  1/ 7/1993  @  0:25
 input file:   C:\DM40\INPUT40\DR2K12.LIS
 parameters:    free drainage           and yields calculated
               drain spacing =     610. cm   drain depth =  102.0 cm
--------------------------------------------------------------------------------
```

YEAR	RAINFALL	INFILTR	ET	DRAIN	RUNOFF	DRYDAYS	WORKDAYS	SEW	PUMP VOL
1958	51.00	51.00	44.91	11.91	.00	28.00	98.80	.0	.00
1959	95.83	95.83	56.58	38.41	.00	31.00	87.28	.0	.00
1960	56.97	56.97	40.54	18.54	.00	46.00	98.00	.0	.00
1961	77.57	77.57	52.37	24.01	.00	27.00	93.25	.0	.00
1962	59.16	59.16	39.83	19.45	.00	52.00	87.83	.0	.00
1963	45.92	45.92	35.60	10.20	.00	56.00	98.00	.0	.00
1964	62.46	62.46	43.87	18.54	.00	37.00	95.17	.0	.00
1965	65.51	65.51	40.20	25.12	.00	53.00	100.03	.0	.00
1966	52.17	52.17	35.01	17.23	.00	61.00	99.20	.0	.00
1967	76.94	76.94	42.91	33.97	.00	40.00	95.90	.0	.00
1968	86.11	86.11	53.71	31.66	.00	13.00	100.58	.0	.00
1969	72.59	72.59	43.84	29.83	.00	13.00	94.92	.0	.00
1970	75.39	75.39	51.32	24.00	.00	26.00	91.40	.0	.00
1971	67.36	67.36	42.35	23.21	.00	34.00	97.47	.0	.00
1972	96.60	96.60	55.29	40.94	.00	14.00	81.55	.0	.00
1973	84.79	84.79	44.26	42.04	.00	42.00	91.42	.0	.00
1974	82.27	82.27	38.19	43.99	.00	49.00	95.90	.3	.00
1975	115.27	115.27	56.09	59.37	.00	26.00	83.61	.0	.00
1976	81.69	81.69	44.44	37.69	.00	40.00	88.87	.0	.00
1977	73.30	73.30	51.55	21.76	.00	42.00	88.75	.0	.00
1978	60.17	60.17	39.56	17.75	.00	60.00	91.97	.0	.00
1979	64.06	64.06	43.97	22.61	.00	23.00	105.00	.0	.00
1980	80.98	80.98	54.51	25.90	.00	18.00	90.85	.0	.00
1981	86.51	86.51	53.65	33.20	.00	35.00	86.48	.0	.00
1982	72.34	72.34	46.06	26.54	.00	37.00	98.70	.0	.00
1983	81.64	81.64	50.99	30.83	.00	33.00	81.50	.0	.00
1984	76.58	76.58	46.76	27.77	.00	46.00	88.28	.0	.00
1985	103.17	103.17	52.54	52.72	.00	36.00	85.40	.0	.00
1986	95.43	95.43	57.33	38.26	.00	23.00	84.98	.0	.00
1987	74.27	74.27	51.53	22.63	.00	69.00	92.38	.0	.00
1988	70.21	70.21	43.52	26.24	.00	74.00	98.00	.0	.00
1989	82.14	82.14	55.55	25.95	.00	20.00	90.53	.0	.00
1990	84.02	84.02	47.68	36.24	.00	43.00	91.33	.0	.00
AVG	76.07	76.07	47.17	29.05	.00	37.79	92.53	.0	.00

I2: DR30 - Drainage Only at 30-Ft Tile Spacings

```
********************************************************************************
----------RUN STATISTICS ----------          time:  1/ 7/1993 @  0:29
 input file:   C:\DM40\INPUT40\DR3K12.LIS
 parameters:    free drainage           and yields calculated
               drain spacing =     914. cm   drain depth =  102.0 cm
-------------------------------------------------------------------------------
```

YEAR	RAINFALL	INFILTR	ET	DRAIN	RUNOFF	DRYDAYS	WORKDAYS	SEW	PUMP VOL
1958	51.00	51.00	45.08	11.49	.00	27.00	98.80	.0	.00
1959	95.83	95.83	57.06	37.34	.00	30.00	87.28	.0	.00
1960	56.97	56.97	40.73	19.04	.00	46.00	98.00	.0	.00
1961	77.57	77.57	52.56	23.60	.00	27.00	93.25	.0	.00
1962	59.16	59.16	40.22	19.21	.00	48.00	87.83	.0	.00
1963	45.92	45.92	35.84	9.96	.00	56.00	97.00	.0	.00
1964	62.46	62.46	44.10	18.13	.00	35.00	95.17	.0	.00
1965	65.51	65.51	40.47	24.46	.00	53.00	100.03	.0	.00
1966	52.17	52.17	35.12	17.47	.00	61.00	99.20	.0	.00
1967	76.94	76.94	43.31	33.34	.00	40.00	95.90	.0	.00
1968	86.11	86.11	53.94	31.14	.00	13.00	100.58	.0	.00
1969	72.59	72.59	43.98	30.39	.00	11.00	94.92	.0	.00
1970	75.39	75.39	51.63	23.57	.00	26.00	91.40	.0	.00
1971	67.36	67.36	42.48	22.52	.00	33.00	97.47	.0	.00
1972	96.60	96.60	55.35	40.96	.00	14.00	81.55	.0	.00
1973	84.79	84.79	44.48	41.82	.00	41.00	91.42	.0	.00
1974	82.27	82.27	38.77	43.78	.00	47.00	95.90	11.1	.00
1975	115.27	115.27	56.25	59.07	.00	26.00	83.14	.0	.00
1976	81.69	81.69	44.76	37.61	.00	39.00	88.33	.0	.00
1977	73.30	73.30	51.81	21.39	.00	42.00	88.75	.0	.00
1978	60.17	60.17	39.78	17.46	.00	60.00	91.97	.0	.00
1979	64.06	64.06	44.15	22.19	.00	23.00	105.00	.0	.00
1980	80.98	80.98	55.08	25.44	.00	18.00	90.85	.0	.00
1981	86.51	86.51	53.88	33.18	.00	35.00	86.48	.0	.00
1982	72.34	72.34	46.39	26.02	.00	35.00	98.70	.0	.00
1983	81.64	81.64	51.23	30.74	.00	33.00	81.50	.0	.00
1984	76.58	76.58	47.11	26.87	.00	46.00	88.28	.0	.00
1985	103.17	103.17	52.75	53.12	.00	35.00	85.36	.0	.00
1986	95.43	95.43	57.55	38.14	.00	23.00	84.18	.0	.00
1987	74.27	74.27	51.70	22.22	.00	69.00	92.38	.0	.00
1988	70.21	70.21	43.63	26.07	.00	74.00	98.00	.0	.00
1989	82.14	82.14	55.76	25.98	.00	20.00	90.53	.0	.00
1990	84.02	84.02	48.17	35.23	.00	42.00	91.33	.0	.00
AVG	76.07	76.07	47.43	28.76	.00	37.21	92.44	.3	.00

I3: DR60 - Drainage Only at 60-Ft Tile Spacings

****

----------RUN STATISTICS ----------   time: 1/ 7/1993 @ 0:20
input file: C:\DM40\INPUT40\DR6K12.LIS
parameters: free drainage   and yields calculated
               drain spacing =   1830. cm   drain depth = 102.0 cm

YEAR	RAINFALL	INFILTR	ET	DRAIN	RUNOFF	DRYDAYS	WORKDAYS	SEW	PUMP VOL
1958	51.00	51.00	46.09	10.32	.00	26.00	98.80	.0	.00
1959	95.83	95.83	59.27	33.54	.00	25.00	87.28	.0	.00
1960	56.97	56.97	41.92	19.73	.00	41.00	98.00	.0	.00
1961	77.57	77.57	53.52	21.54	.00	23.00	90.75	.0	.00
1962	59.16	59.16	42.28	17.57	.00	41.00	87.83	.0	.00
1963	45.92	45.92	37.57	8.79	.00	48.00	96.30	.0	.00
1964	62.46	62.46	45.71	15.77	.00	31.00	95.17	.0	.00
1965	65.51	65.51	41.48	22.35	.00	52.00	100.03	.0	.00
1966	52.17	52.17	36.01	17.22	.00	56.00	99.20	.0	.00
1967	76.94	76.94	45.05	30.98	.00	35.00	93.43	.0	.00
1968	86.11	86.11	54.68	30.13	.00	13.00	100.58	.0	.00
1969	72.59	72.59	44.81	30.74	.00	7.00	91.12	30.1	.00
1970	75.39	75.39	53.21	21.69	.00	26.00	91.40	.0	.00
1971	67.36	67.36	43.52	20.49	.00	32.00	96.47	.0	.00
1972	96.60	96.60	55.73	40.63	.00	11.00	76.85	.0	.00
1973	84.79	84.79	46.38	39.94	.00	37.00	91.42	.0	.00
1974	82.27	82.27	41.36	41.89	.00	38.00	93.72	65.7	.00
1975	115.27	115.27	57.18	57.64	.00	23.00	74.29	.0	.00
1976	81.69	81.69	46.39	36.84	.00	27.00	82.11	15.0	.00
1977	73.30	73.30	53.42	19.49	.00	37.00	88.75	.0	.00
1978	60.17	60.17	40.84	16.60	.00	58.00	91.97	.0	.00
1979	64.06	64.06	45.08	20.49	.00	21.00	105.00	.0	.00
1980	80.98	80.98	56.14	24.77	.00	17.00	90.85	.0	.00
1981	86.51	86.51	55.44	32.02	.00	27.00	82.12	.0	.00
1982	72.34	72.34	47.64	24.22	.00	34.00	98.70	.0	.00
1983	81.64	81.64	53.11	29.10	.00	27.00	80.50	.0	.00
1984	76.58	76.58	48.92	24.27	.00	41.00	88.28	.0	.00
1985	103.17	103.17	54.10	52.73	.00	34.00	83.18	.0	.00
1986	95.43	95.35	58.71	37.03	.07	21.00	79.39	.0	.00
1987	74.27	74.27	52.74	20.56	.00	69.00	92.38	.0	.00
1988	70.21	70.21	44.95	25.14	.00	72.00	98.00	.0	.00
1989	82.14	82.14	56.58	25.52	.00	19.00	90.53	.0	.00
1990	84.02	84.02	50.09	32.44	.00	30.00	91.33	.0	.00
AVG	76.07	76.07	48.79	27.34	.00	33.30	91.08	3.4	.00

I4: SI20 - Subirrigation at 20-Ft Tile Spacings

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***************************************************************************************
----------RUN STATISTICS ----------          time:  1/ 7/1993 @  0:34
 input file:    C:\DM40\INPUT40\SI2K12.LIS
 parameters:     subirrigation run       and yields calculated
                drain spacing =     610. cm   drain depth =  102.0 cm
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YEAR	RAINFALL	INFILTR	ET	DRAIN	RUNOFF	DRYDAYS	WORKDAYS	SEW	PUMP VOL
1958	51.00	51.00	52.77	4.05	.00	21.00	98.80	.0	-16.92
1959	95.83	95.83	62.30	32.70	.00	12.00	87.28	72.3	-20.78
1960	56.97	56.97	52.78	5.32	.00	14.00	98.00	.0	-20.71
1961	77.57	77.57	56.15	21.21	.00	13.00	93.25	.0	-19.15
1962	59.16	59.16	52.40	6.88	.00	26.00	87.33	.5	-18.37
1963	45.92	45.92	55.35	-9.59	.00	5.00	96.30	.0	-26.31
1964	62.46	62.46	55.30	7.15	.00	14.00	95.17	4.8	-19.06
1965	65.51	65.51	56.21	9.11	.00	22.00	99.03	.0	-24.36
1966	52.17	52.17	53.51	-1.28	.00	11.00	99.20	.0	-24.95
1967	76.94	76.94	55.03	21.86	.00	16.00	93.30	9.0	-19.25
1968	86.11	86.11	54.74	30.63	.00	13.00	100.58	112.6	-17.06
1969	72.59	72.59	48.02	25.65	.00	4.00	94.92	41.8	-14.32
1970	75.39	75.39	58.42	16.90	.00	14.00	91.40	26.4	-16.91
1971	67.36	67.36	54.95	10.61	.00	10.00	96.47	.7	-19.92
1972	96.60	96.60	55.74	40.48	.00	14.00	81.55	65.8	-15.12
1973	84.79	84.79	58.94	27.36	.00	5.00	91.42	.0	-20.46
1974	82.27	82.27	54.53	27.64	.00	8.00	95.90	7.2	-19.33
1975	115.27	113.14	60.99	52.35	2.13	8.00	81.51	11.5	-19.27
1976	81.69	81.69	58.03	24.10	.00	3.00	87.57	66.2	-20.57
1977	73.30	73.30	58.94	14.37	.00	29.00	88.75	.2	-18.97
1978	60.17	60.17	59.03	-1.72	.00	12.00	91.97	.0	-24.06
1979	64.06	64.06	51.18	15.40	.00	12.00	105.00	39.7	-19.89
1980	80.98	80.98	55.77	24.64	.00	18.00	90.85	45.2	-15.57
1981	86.51	86.51	58.81	28.03	.00	12.00	86.48	.0	-18.40
1982	72.34	72.34	56.80	15.80	.00	19.00	98.70	.0	-18.67
1983	81.64	81.64	63.89	17.93	.00	7.00	80.50	9.1	-20.69
1984	76.58	76.58	60.96	13.57	.00	14.00	87.28	.0	-22.00
1985	103.17	103.17	58.46	46.81	.00	15.00	83.32	.0	-19.79
1986	95.43	95.43	59.01	36.58	.00	14.00	84.88	.2	-17.24
1987	74.27	74.27	65.71	8.45	.00	20.00	92.38	.0	-27.73
1988	70.21	70.21	62.19	7.57	.00	31.00	98.00	.0	-27.69
1989	82.14	82.14	55.94	25.55	.00	20.00	90.53	6.0	-16.25
1990	84.02	84.02	60.71	23.20	.00	11.00	91.33	.0	-18.17
AVG	76.07	76.01	57.08	19.07	.06	14.15	92.09	15.7	-19.94

I5: SI30 - Subirrigation at 30-Ft Tile Spacings

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*********************************************************************************
----------RUN STATISTICS ----------          time:  1/ 7/1993 @  0:43
 input file:   C:\DM40\INPUT40\SI3K12.LIS
 parameters:    subirrigation run       and yields calculated
               drain spacing =     914. cm   drain depth =  102.0 cm
---------------------------------------------------------------------------------
```

YEAR	RAINFALL	INFILTR	ET	DRAIN	RUNOFF	DRYDAYS	WORKDAYS	SEW	PUMP VOL
1958	51.00	51.00	52.88	3.68	.00	21.00	98.80	.0	-14.40
1959	95.83	95.83	62.40	32.13	.00	11.00	87.28	48.2	-17.70
1960	56.97	56.97	52.98	5.65	.00	15.00	98.00	.0	-19.24
1961	77.57	77.57	56.37	20.88	.00	13.00	93.25	.0	-16.60
1962	59.16	59.16	52.02	7.37	.00	24.00	87.33	1.8	-14.97
1963	45.92	45.92	55.41	-9.73	.00	7.00	96.30	.0	-23.81
1964	62.46	62.46	54.76	7.58	.00	14.00	95.17	.0	-15.46
1965	65.51	65.51	56.25	8.76	.00	22.00	99.03	.0	-22.42
1966	52.17	52.17	53.01	-.46	.00	11.00	99.20	.0	-22.36
1967	76.94	76.94	54.36	22.31	.00	19.00	93.30	5.4	-16.14
1968	86.11	86.11	55.06	30.04	.00	13.00	100.58	68.7	-13.51
1969	72.59	72.59	47.92	26.37	.00	4.00	94.92	30.5	-10.50
1970	75.39	75.39	58.54	16.68	.00	14.00	91.40	26.0	-13.78
1971	67.36	67.36	54.77	10.29	.00	10.00	96.47	.0	-16.45
1972	96.60	96.60	55.69	40.62	.00	14.00	81.55	53.5	-12.27
1973	84.79	84.79	58.58	27.72	.00	5.00	91.42	.0	-17.76
1974	82.27	82.27	54.87	27.64	.00	7.00	95.76	24.5	-17.74
1975	115.27	113.35	60.99	52.44	1.92	8.00	81.14	.6	-15.70
1976	81.69	81.69	57.70	24.65	.00	3.00	87.13	8.1	-17.65
1977	73.30	73.30	58.93	14.30	.00	29.00	88.75	.0	-15.42
1978	60.17	60.17	58.10	-.87	.00	12.00	91.97	.0	-22.08
1979	64.06	64.06	51.25	15.13	.00	12.00	105.00	2.1	-16.60
1980	80.98	80.98	55.87	24.63	.00	17.00	90.85	14.0	-12.39
1981	86.51	86.51	58.85	28.19	.00	12.00	86.23	.0	-14.95
1982	72.34	72.34	56.80	15.64	.00	20.00	98.70	.0	-15.94
1983	81.64	81.64	64.14	17.81	.00	7.00	80.50	2.1	-17.09
1984	76.58	76.58	61.09	12.94	.00	14.00	87.28	.0	-18.80
1985	103.17	103.17	58.57	47.23	.00	15.00	82.84	.0	-16.93
1986	95.43	95.43	59.09	36.58	.00	14.00	84.05	.0	-13.83
1987	74.27	74.27	65.66	8.30	.00	20.00	92.38	.0	-25.53
1988	70.21	70.21	61.99	7.70	.00	31.00	98.00	.0	-25.41
1989	82.14	82.14	56.12	25.59	.00	20.00	90.53	4.9	-12.07
1990	84.02	84.02	60.80	22.65	.00	7.00	91.33	.0	-15.66
AVG	76.07	76.01	57.02	19.11	.06	14.09	92.01	8.8	-17.01

I6: SI60 - Subirrigation at 60-Ft Tile Spacings

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******************************************************************************
----------RUN STATISTICS ----------          time:  1/ 7/1993 @  0:38
 input file:   C:\DM40\INPUT40\SI6K12.LIS
 parameters:    subirrigation run       and yields calculated
               drain spacing =    1830. cm   drain depth =  102.0 cm
------------------------------------------------------------------------------
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YEAR	RAINFALL	INFILTR	ET	DRAIN	RUNOFF	DRYDAYS	WORKDAYS	SEW	PUMP VOL
1958	51.00	51.00	51.95	3.90	.00	21.00	98.80	.0	-7.83
1959	95.83	95.83	63.12	30.25	.00	10.00	87.12	.0	-9.31
1960	56.97	56.97	50.82	9.20	.00	13.00	98.00	.0	-11.10
1961	77.57	77.57	57.54	19.07	.00	11.00	90.75	.0	-10.17
1962	59.16	59.16	49.60	10.22	.00	20.00	87.33	1.8	-7.27
1963	45.92	45.92	46.13	-.56	.00	29.00	96.30	.0	-9.89
1964	62.46	62.46	52.76	9.22	.00	13.00	95.17	.0	-8.06
1965	65.51	65.51	50.44	13.69	.00	30.00	100.03	.0	-11.03
1966	52.17	52.17	44.97	8.27	.00	30.00	99.20	.0	-10.36
1967	76.94	76.94	52.17	23.93	.00	22.00	90.83	.0	-8.54
1968	86.11	86.11	56.35	28.46	.00	13.00	100.58	43.0	-6.17
1969	72.59	72.59	47.92	27.61	.00	1.00	90.99	30.2	-4.24
1970	75.39	75.39	58.90	16.02	.00	14.00	91.40	.0	-7.37
1971	67.36	67.36	52.07	11.89	.00	10.00	96.47	.0	-10.40
1972	96.60	96.60	56.02	40.40	.00	11.00	74.15	1.3	-6.86
1973	84.79	84.79	54.69	31.64	.00	9.00	91.42	.0	-9.38
1974	82.27	82.27	50.84	32.40	.00	12.00	92.83	72.1	-9.97
1975	115.27	114.89	61.22	53.25	.37	8.00	73.89	.0	-7.35
1976	81.69	81.69	54.74	28.46	.00	9.00	80.81	15.0	-8.85
1977	73.30	73.30	59.32	13.62	.00	27.00	88.75	.0	-9.38
1978	60.17	60.17	49.88	7.46	.00	41.00	91.97	.0	-10.61
1979	64.06	64.06	50.67	14.95	.00	12.00	105.00	.0	-9.38
1980	80.98	80.98	56.53	24.43	.00	17.00	90.85	.0	-7.00
1981	86.51	86.51	59.45	28.03	.00	7.00	79.76	.0	-9.02
1982	72.34	72.34	55.04	16.81	.00	20.00	98.70	.0	-9.33
1983	81.64	81.64	61.44	20.76	.00	8.00	80.50	.0	-9.13
1984	76.58	76.58	57.92	15.26	.00	15.00	85.62	.0	-10.02
1985	103.17	103.17	59.45	47.39	.00	15.00	80.50	.0	-10.20
1986	95.43	94.65	59.79	35.25	.78	14.00	76.83	.0	-7.44
1987	74.27	74.27	57.67	15.64	.00	62.00	92.38	.0	-7.38
1988	70.21	70.21	47.43	22.66	.00	65.00	98.00	.0	-3.80
1989	82.14	82.14	56.92	25.17	.00	19.00	89.88	.0	-5.46
1990	84.02	84.02	58.64	23.89	.00	8.00	90.25	.0	-9.14
AVG	76.07	76.04	54.62	21.47	.03	18.67	90.46	5.0	-8.53

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