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WATER TABLE MANAGEMENT TO
MAXIMIZE THE ECONOMIC EFFICIENCY
OF BIOMASS PRODUCTION

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Harold Walter Belcher

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WATER TABLE MANAGEMENT TO MAXIMIZE THE ECONOMIC EFFICIENCY OF BIOMASS PRODUCTION

By

Harold Walter Belcher

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ABSTRACT

WATER TABLE MANAGEMENT TO
MAXIMIZE THE ECONOMIC EFFICIENCY
OF BIOMASS PRODUCTION

By

Harold Walter Belcher

For hundreds of years throughout the world, agricultural producers have used underground drainage pipe systems to improve crop production by removing excess soil water from the soil profile within the root zone (Weaver, 1964). Agricultural producers and scientists have recently shown underground drainage pipe systems can also be used as water table management systems to provide water to crops during rainfall deficit periods.

The objectives of this research are to: 1) quantify water table management operation parameters that influence plant biomass production and 2) develop a model for the efficient design of water table management systems that will allow the systems to be operated for maximum plant biomass production economic efficiency.

Through field research it was confirmed that corn and soybean production is sensitive to mean water table depth and water table fluctuation. The field research results suggest the best operation strategy for subirrigating field

crops is: (1) establish a water table depth immediately following seeding, (2) for soybean production maintain that depth until crop maturity and for corn production raise the water periodically for short time periods during the growing season, (3) at crop maturity put the system into the subsurface drainage mode and maintain it in that mode until after harvest and (4) repeat the cycle the next spring.

For the second objective, a mathematical model for determining water table management system design proportions and efficiently transforming those design proportions to system installation requirements was developed and tested. The model establishes the optimum lateral spacing for both the subsurface drainage and subirrigation modes. A steady state saturated groundwater flow formulation is used to determine lateral spacing needed for subsurface drainage and to maintain the water table at design depth during peak evapotranspiration without rainfall during subirrigation. A nonsteady, falling water table analysis is made to adjust the lateral spacing, if needed, to handle precipitation events that occur during subirrigation operation.

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TABLE OF CONTENTS

LIST OF APPENDICES

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

adfi	water table fluctuation dry stress index for August, m*h/h
ANEV	the net annual equivalent monetary value of an economic analysis alternate
ASI	economic analysis annual system monetary income
ASC	economic analysis annual system monetary cost
atimea	percentage of time water table is above the mean water table during month of August, %
atimeb	percentage of time water table is below the mean water table during month of August, %
awfi	water table fluctuation wet stress index for August, m*h/h
awtd	mean depth to the water table during month of August, m
cyield	relative corn yield, %
jdfi	water table fluctuation dry stress index for July, m*h/h
jtimea	percentage of time water table is above the mean water table during month of July, %
jtimeb	percentage of time water table is below the mean water table during month of July, %
jwfi	water table fluctuation wet stress index for July, m*h/h
jwtd	mean depth to the water table during month of July, m
MARR	economic analysis interest rate that represents the minimum attractive rate of return required by the investor
P	the monetary installed cost of a water table management system used for economic analysis
p	probability that linear regression equation result is due to chance as determined by a single tailed F statistic test for significance

r^2	linear regression correlation coefficient squared
sdfi	water table fluctuation dry stress index for the season, m*h/h
spacing	distance between parallel subsurface drain pipes, m
stimea	percentage of time water table is above the mean water table from start of monitoring period to end of monitoring period, %
stimeb	percentage of time water table is below the mean water table from start of annual monitoring period to end of annual monitoring period, %
swfi	water table fluctuation wet stress index for the season, m*h/h
swtd	mean depth to the water table from start of annual monitoring period to end of annual monitoring period, m
syield	relative soybean yield, %

INTRODUCTION

Many agriculturally productive soils in the United States and the world have a naturally occurring shallow water table that fluctuates during the growing season.

Subsurface Drainage

Underground subsurface drainage pipe is used to lower the water table. In the United States the subsurface drainage systems are installed at about 1 m depth. The agricultural benefits of removing excess water from the soil profile using below ground drainage pipe systems (i.e. subsurface drainage) are well documented (Pavelis, 1987). Agricultural producers install below ground drainage pipe systems for many reasons: to remove excess soil water, to reduce diseases of crops, livestock and people, to remove excess accumulations of undesirable salts, to reduce erosion and to reduce delays in seeding and harvesting. The soil surface warms earlier in the spring and field operations can be performed earlier without soil structure damage.

Over the years, subsurface drainage system variables such as pipe depth, pipe spacing and flow capacity have been determined by one of three methods: past experience in similar soils, drainage equations and computer simulation models.

Today, in the United States, the most common method of designing subsurface drainage system variables for a site is to evaluate the site soils and topography and then use design dimensions that have been used in the region for similar soil and topography situations. Generally, the soil at the site is evaluated by combining information received from the site owner with a United States Department of Agriculture Soil Conservation Service (SCS) soil survey map and narrative information for the site. Occasionally this is supplemented with on-site soil investigation (to approximately 1 m) by borings using hand operated soil augers or test pits excavated with a backhoe. The topography of the site is evaluated by topographic surveying and mapping techniques.

Using this information, the system designer establishes design proportions based upon his or her past experience in similar situations and/or information provided by drainage guides for the area.

The second most popular procedure for designing subsurface drainage systems is by using drainage equations. These relatively simple equations relate pipe spacing and depth to water table elevation or drainage rate. Drainage equations based upon a fixed water table profile assume steady state conditions. The best known steady state equations were developed by Hooghoudt and Ernst (Van Beers, 1976). Drainage equations that relate design variables to the rate of fall of the water table are commonly called transient method equations. These equations were developed by Glover (Dumm, 1954), Bouwer and van Schilfgaarde (1963) and others. Both type equations, steady state and transient, require a knowledge of the hydraulic conductivity of the soil and depth from the surface to the restricting layer. The steady state equations also require knowledge of the appropriate steady state drainage rate for the crops to be drained and the site location. The transient equations require knowledge of the appropriate rate of water table drawdown for the crops to be drained and the site location.

In actual practice the steady state method is used more often than transient analysis. Drainage guides provide recommended drain pipe spacing based upon soil type. Those spacings have been established using a steady state equation. Also, the pipes that deliver the drainage water from the parallel pipes (laterals) to the site outlet are sized for a steady state design drainage rate.

Recently, computer programs to simulate subsurface drainage system performance have been developed and been shown to be applicable to the design process. The simulation models vary in complexity, input data requirements and ease of use. Examples of computer simulation models being used for subsurface drainage system design are DRAINMOD (Skaggs, 1978), the SWATRE model (Feddes et al. 1978; Belmans et al. 1983) and the WATRCOM model (Parsons, 1987).

DRAINMOD is based on a one dimensional (vertical) water balance within the soil profile and at the soil surface.

The SWATRE model is based on solving the Richard's equation (Richards, 1931) for combined saturated-unsaturated flow in the vertical direction only. For drainage system design, the SWATRE model is linked with other models to predict trafficability, germination, emergence, crop growth and production (van Wijk and Feddes, 1986).

The WATRCOM model links a finite element solution of the two-dimensional Boussinesq equation for the saturated zone below the water table with a vertical water balance for the unsaturated zone above the water table. The Boussinesq equation as used in the WATRCOM model is defined by Parsons, 1987.

Water Table Management

For many crops and soil textures, experience and research has shown a constant 0.8 to 1.2 m depth to the water table is near the optimum for corn production (Goins et al., 1966; Williamson and Kriz, 1970). However, when rainfall during the growing season is less than the volume needed by the crop, the water table falls below the 1.2 m depth and water deficit stress can reduce plant biomass production. This deficiency may be overcome by irrigation; however, the economic return on irrigation system investment via traditional sprinkler type systems is limited due to the fact that relatively high average yields are obtained without irrigation.

Skaggs (1978) has shown that underground pipe used for drainage can often be used to provide water to the soil profile during rainfall deficit times at very little increased cost. This practice is called subirrigation and the field system is a water table management system (see Figure 1).

A water table management system that combines subirrigation with subsurface drainage potentially provides an ideal root zone soil water regime. The system operating in the subsurface drainage mode drains excess water from the root

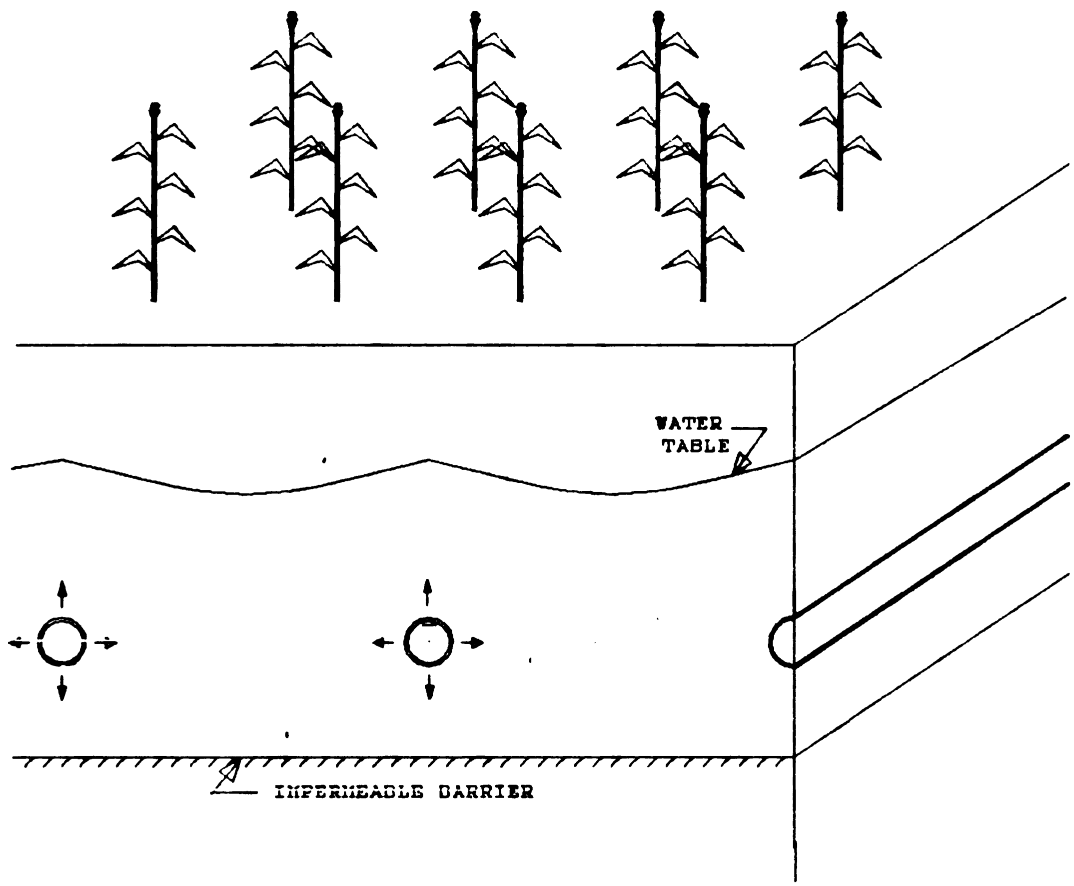


Figure 1. Cross sectional schematic of a water table management system operating in a subirrigation mode.

zone following rainfall events. The system operating in the subirrigation mode establishes and maintains a water table near the bottom of the crop root zone from which water moves by capillarity into the root zone thus preventing stress due to a deficit matrix potential. Because capillarity is a function of soil water potential, a function of the soil water content, the plant controls the irrigation rate and timing. Thus, for a constant depth to the water table, the plants schedule the irrigation based upon physiological needs.

This reasoning leads to the obvious conclusion that the optimum water table management system for plant biomass production is one in which the water table is: a) maintained near the soil surface from seeding to germination, b) lowered at the optimum root length development rate, to an optimum depth for the crop and c) maintained at that depth until the crop matures. Thus the system for maximum production would have pipe sizes large enough to drain excess water at the maximum rainfall rate and provide subirrigation water at the maximum evapotranspiration rate. In addition the pipe laterals would be spaced so as to allow for saturated flow between the pipe to midway between pipes at maximum rainfall rate and maximum evapotranspiration rate with only a slight water table surface elevation difference.

A water table management system is operated in a subsurface drainage mode during tillage and harvest times. This causes the water table to be at or near the pipe depth and thus reduces the potential for soil compaction due to field operations. During the growing season, a properly designed system allows the water table to be maintained at the desired depth for optimum crop production. During this time period, the system will be in a drainage mode during times of excess rainfall and in an irrigation mode when rainfall does not meet the evapotranspiration needs of the crop.

At the present time, the design methods used to establish water table management system pipe depth, spacing and flow capacity are established for a specific site by one or a combination of three methods. For the most part the parallel pipe spacings are established by modifying the spacing that would be used at the site for subsurface drainage. The factor most often used is to multiply the recommended drainage spacing by 0.7. The multiplication factor may be adjusted based upon the United States Department of Agricultural (USDA) classification for the soil in the profile as shown in Table 1 (Doty et al., 1986).

Table 1. Multiplication factor for water table management system lateral spacing as a function of USDA soil classification.

SOIL TYPE	HYDRAULIC CONDUCTIVITY	MULTIPLICATION FACTOR
C-SiL	0 - 0.5 m/d	0 - 0.61
SCL & L	0.5 - 1.5 m/d	0.61 - 0.77
SL	1.5 - 3.0 m/d	0.77 - 0.85
LS	3.0 - 6.0 m/d	0.85 - 0.91

A second method of determining lateral spacing is to calculate the spacing using a modification of a steady state equation developed by Hooghoudt and Ernst (Van Beers, 1976).

The third method is to simulate the performance of water table management systems. By varying the system design variables, the simulation model may be used to determine the best combination of those variables. The simulation models for subsurface drainage (DRAINMOD and WATRCOM) have the capability of modeling drainage, controlled drainage and subirrigation. Often the first two design methods are used to establish the initial system proportions for subsequent simulation. The simulation model DRAINMOD is most frequently used for water table management system design. The applicability of the model for that purpose has been documented by Mostaghimi et al. (1985), Evans and Skaggs (1987) and others.

Recently, attention has been given to using the simulation models to develop water table management system design dimension guidelines for benchmark soils within a given region (Skaggs and Tabrizi, 1986).

It is likely the key element of a water table management system design is to economically control the fluctuation of the water table following rainfall events. For this the system designer must determine the lateral spacing and pipe sizes that will limit yield reduction due to water table rise. The cost of limiting water table fluctuation and thus reduced yield must be balanced against the cost of the system. Thus we need to determine how close should the laterals be spaced to obtain the maximum return on the system cost when a rainfall event occurs while in the subirrigation mode.

The computer simulation models available have the capability of assisting with the design for a site on the basis of transient system operation and economic return on investment. However, because their use requires multiple runs and detailed soil and weather data often not available, application of the models for water table management system design has been limited.

Research Objectives

The overall goal of this research is to develop a water table management system design process suitable for use by system designers with limited technical training in porous media flow and in computer simulation modeling. The design process should be site specific, should provide realistic output using input data that is readily available, and should be operational on computing systems not exceeding personal computer capability.

The specific research objectives are to:

1. Quantify water table management operation parameters that influence plant biomass production.

2. Develop a model for the efficient design of water

table management systems that will allow the system to be operated for maximum plant biomass production economic efficiency.

To arrive at the design process that follows, it was necessary to quantify the effect on yield of a fluctuating water table. A field study, described subsequently, contributed to that process. The data from the field study were used to establish relationships between corn and soybean yield vs. water table depth and fluctuation. This allowed the formulation of water table management parameters (design water table depth and time limits to return the water table to design depth following rainfall events that caused soil profile saturation) in terms of economic benefit. A computer model was then developed to translate these parameters to system installation requirements.

LITERATURE REVIEW

The adverse effects of excess soil water on corn and sorghum production has been widely studied and reported: Williamson and van Schilfgaarde (1965), Goins et al. (1966), Ritter and Beer (1969), Lal and Taylor (1969; 1970), DeBoer and Ritter (1970), Williamson and Carreker (1970), Purvis and Williamson (1972), Follett et al. (1974), Chaudhary et al. (1975), Howell and Hiler (1974), Howell et al. (1976), Zolezzi et al. (1978), Benz et al. (1978), Singh and Ghildyal (1980), Fausey et al. (1985) and Fausey and McDonald, Jr. (1985). These studies assume either a flooded condition or a constant depth to the water table during the study period. Generally, the studies confirm that extended flooding reduces grain yield and that reduction is greatest during emergence and early growth stages.

Zolezzi et al. (1978) found that flooding of grain sorghum in field lysimeters for three durations during the early productive growth stage reduced yield by 2.5 percent, 12.9 percent and 21.9 percent for 7, 12 and 17 day flooding periods, respectively. Purvis and Williamson (1972) concluded that 12 day old corn is severely injured if flooded for more than one day. Lal and Taylor (1969; 1970) concluded that intermittent flooding early in the growing season reduced yield of corn more than did constant water tables of 0.15 m and 0.30 m depth. Other studies have shown that a period of flooding for 48 to 96 h at the four to six leaf vegetative growth stage retarded the growth of corn hybrids (Singh and Ghildyal, 1980). Fausey and McDonald, Jr. (1985) report that a very short period of flooding (48 h to 96 h) reduced field emergence of both hybrid and inbred cultivars.

Constant water table depths giving maximum yields have been reported to be 0.76 m to 0.86 m for corn (Williamson and van Schilfgaarde, 1965). The constant water table studies show that lower water tables with surface irrigation provide better yields than higher water tables when surface water is not applied or applied sparingly (Williamson and Kriz, 1970). Benz et al. (1978) maintained a water table at three depths (between 1 m and 3 m) in a sandy loam soil and applied sprinkler irrigation amounts from 0 (precipitation only) to 1.5 times calculated irrigation requirements. For each of the three years studied, the production of corn grain and total dry weight was highest from the shallow water table (which varied from 1.2 m depth at the start of the growing season to 1.8 m depth at the end of the growing season) and with no irrigation.

The corn studies that address a fluctuating water table (Follett et al., 1974; Chaudhary et al., 1975; Howell and

Hiler, 1974; Howell et al., 1976; Zolezzi et al., 1978) provide useful information but do not lend themselves to development of algorithms suitable to crop growth simulation modeling of fluctuating water table conditions. For those algorithms, quantitative information of the effect of a fluctuating water table on root and shoot growth is needed. Kanwar et al. (1988) provide quantitative data on the effect of a fluctuating water table on corn yield at five different growth stages. They reported yields were significantly reduced when the sum of the daily values of the amount the water table depth was less than 0.30 m exceeded 0.40 m·days during the first growth stage.

The effect of excess water on soybean production has not received much research attention. Williamson and van Schilfgaarde (1965) report constant water table depths from 0.46 m to 0.61 m provide maximum soybean yield. A recent lysimeter study of soybean responses to excess water (VanToai et al., 1987) shows flooding for 10 days at the early vegetative, rapid flowering and early pod filling stages affects the soil oxygen diffusion rate, canopy temperature, photosynthetic rate, leaf water potential, plant height, total leaf area, stem and leaf growth rates and seed yield. Flooding at the rapid flowering and early pod filling stages reduced yield.

The mechanisms of yield reduction due to excess soil water have been the subject of many studies. Patwardhan et al. (1988) provided an excellent review of the research and concepts related to aeration requirements of crops in terms of oxygen diffusion rates and oxygen content as affected by excess soil water conditions. Hiler et al. (1971), McCree (1982) and Grable and Siemer (1968) have shown excess soil water within the root zone affects the respiration capability of the roots by limiting the oxygen uptake and carbon dioxide release and that the reduced respiration capability may reduce plant biomass production. In addition, Wesseling (1974) and Miller and Johnson (1964) point out excessive soil water also affects microbial activity, carbon dioxide evolution, nitrification and nitrogen mineralization. VanToai et al. (1988) found a positive correlation between tolerance of corn to flooding and its ability to produce, or conserve, metabolic energy under stress. They also found that the fluctuation between high and low O_2 levels was more damaging to germination and seedling growth than a constant low O_2 level.

FIELD STUDIES

The literature review indicates field crop biomass production under artificially drained shallow water table conditions is influenced by the average depth to the water table during the growing season. The literature also suggests the growing season fluctuation of the water table may affect biomass production. However, the study of systems that maintain the growing season water table above pipe depth has largely been limited to computer simulation with very little supporting field research.

To quantify the effect of water table depth and fluctuation on field crop yield, field studies were conducted at two sites for two growing seasons to relate water table depth and fluctuation to corn and soybean biomass production.

Methodology

The field study sites are privately owned and operated agricultural fields located in the south central area of the lower peninsula of Michigan.

Bannister Site:

In August 1985, a combination subsurface drainage and

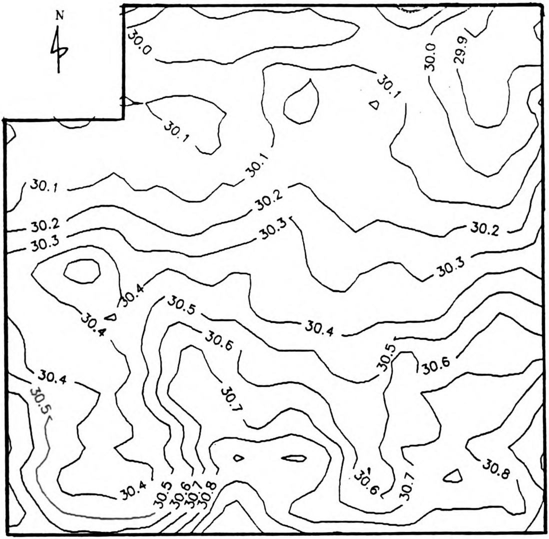


Figure 2. Bannister site topographic map with contours in meters.

subirrigation system in a privately owned 16.2 ha field near Bannister in Gratiot County Michigan (a part of the S.W. 1/4, N.W. 1/4, Section 34, T.9 N., R.1 W.) was installed. The Bannister site is relatively level with the predominant slope toward the northwest (see Figure 2). The soil is mapped as Lenawee series, however, on-site investigation and laboratory analysis by SCS and Michigan State University

(MSU) soil scientists resulted in revising the classification to Ziegenfuss for the entire 16.2 ha. The soil investigation results are given in Appendix A.

The Ziegenfuss series consists of deep, poorly drained soils formed in loamy and clayey calcareous glacial till on till plains and moraines. The surface layer is black silty clay loam 0.15 m deep. The subsoil is dark gray and gray mottled clay 1.15 m thick. The substratum is gray clay and extends to a very dense compacted clay layer at approximately 1.5 m below the surface.

Saturated lateral hydraulic conductivity, by the auger hole method, varied from 10 mm/h to 25 mm/h. The dominate saturated lateral hydraulic conductivity for the site was determined to be 17 mm/h. The auger holes used for hydraulic conductivity testing were 0.1 m diameter, 1.5 m depth and bottomed in the dense clay layer determined to be the impermeable barrier.

The topography of the site allowed subdivision of the area into eight water table management zones in which the surface elevation variance within a zone did not exceed 0.30 m. The subsurface drainage / subirrigation system consists of 102 mm inside diameter (ID) corrugated plastic tubing laterals discharging into corrugated plastic submains and mains

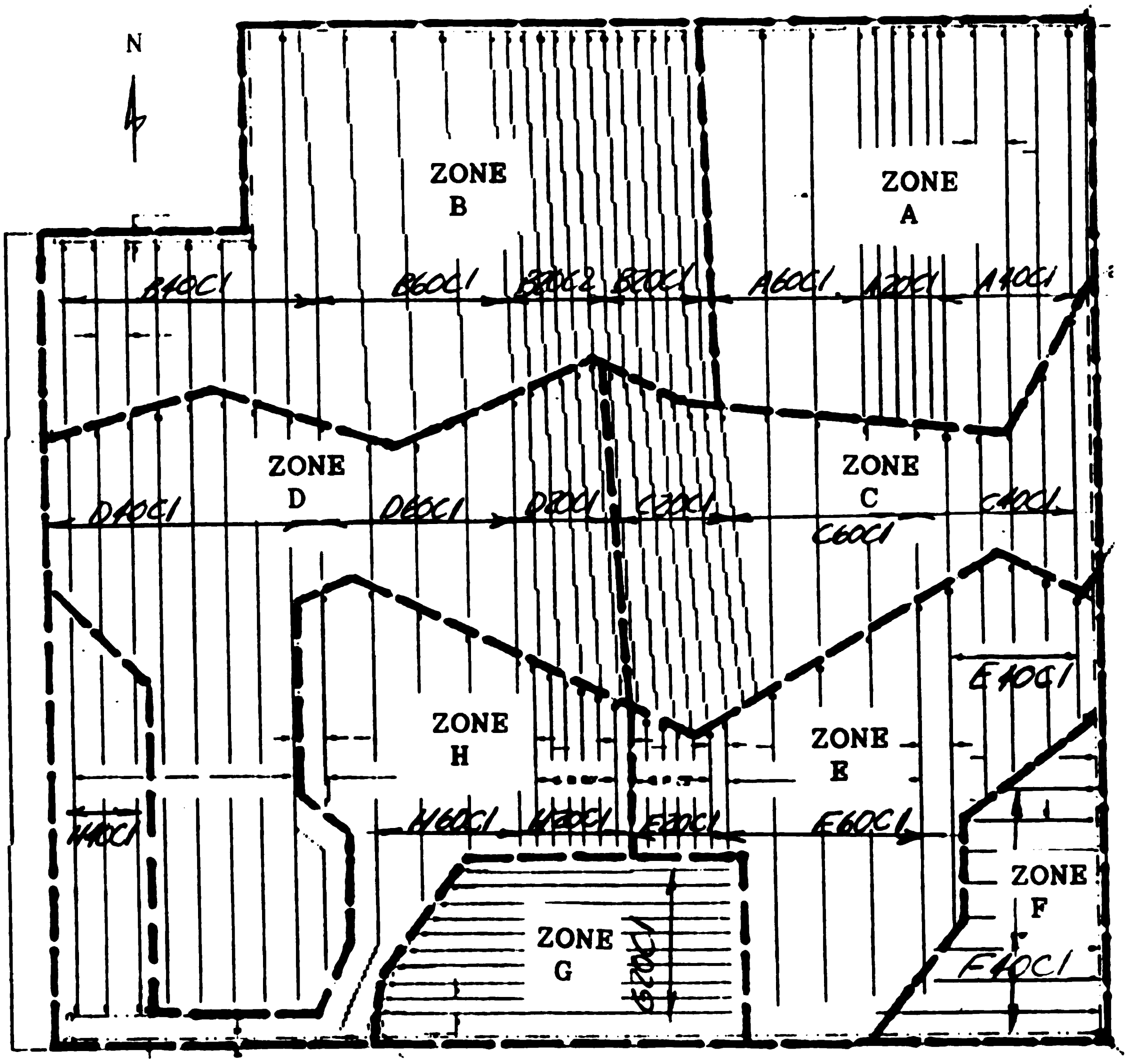


Figure 3. Bannister site water management zones (A through H), subsurface drainage pipe layout (lateral spacing 6, 12, 18 m) and treatments within each zone (for example A40C1).

ranging in size from 127 mm through 305 mm ID. The system was installed August 5-9, 1985 by members of the Michigan Land Improvement Contractors Association. The submains and mains were installed by a trenching machine. The laterals were installed by drainage plows. The laterals are at 6, 12 and 18 m spacing as shown by Figure 3. The depths to the inverts of the laterals vary from 1.1 m to 1.4 m below the ground surface. The system, as installed, provides 8 water table management zones (A through H) and a maximum of 32 irregularly shaped treatment plots that vary in size. The surface elevation (from an arbitrary datum) of the water table management zones is from 29.75 m to 30.18 m for zone A, 29.87 m to 30.18 m for zone B, 30.18 m to 30.48 m for zones C and D, 30.48 m to 30.78 m for zones E and H, and 30.78 m to 31.03 m for zones F an G.

St. Johns Site:

In August 1986, a combination subsurface drainage and subirrigation system was installed in a privately owned 22.2 ha field near St. Johns in Clinton County Michigan (a part of the W. 1/2, S.E. 1/4, Section 30, T.7 N., R.2 W.). The St. Johns site is relatively level with the predominant slope toward the northwest (see Figure 4). The soil in the north half of the site is mapped as Wasepi series and in the south half as Gilford. The on-site investigations and laboratory analysis by SCS and MSU soil scientists resulted in determining the entire research area is Wasepi. The soil investigation results are given in Appendix B.

The Wasepi series consists of somewhat poorly drained soils formed in loamy deposits underlain by sand and gravel at 0.5

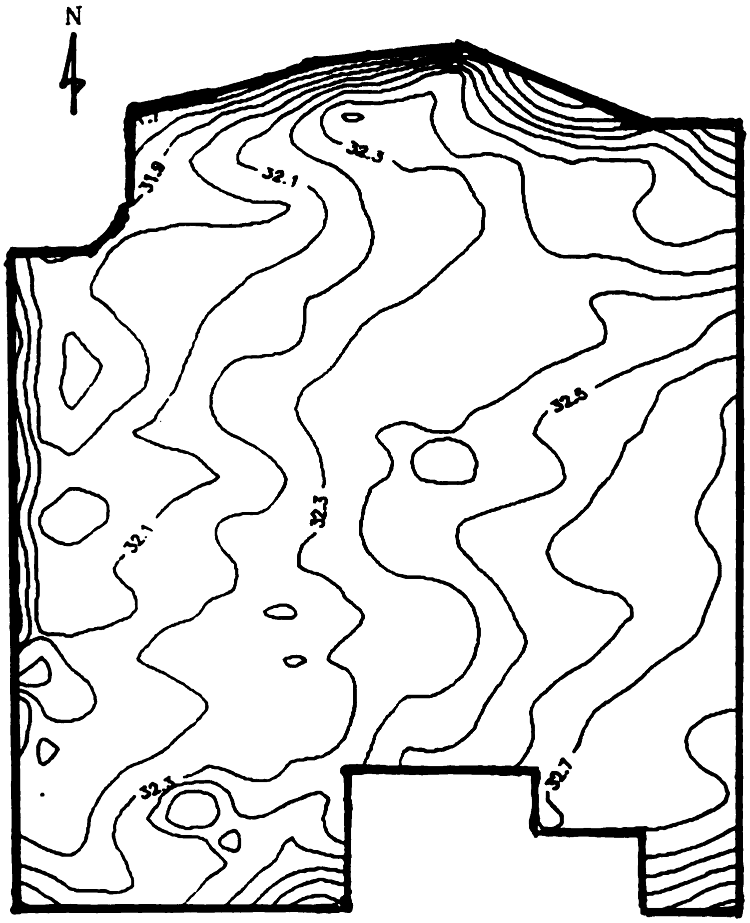


Figure 4. St. Johns site topographic map with contours in meters.

m to 1.0 m. The soils are formed in loamy and sandy glaciofluvial deposits on uplands and have a very dark grayish-brown sandy loam surface layer 0.20 m thick and brown sandy loam subsurface layers 0.13 m thick. The subsoil is mottled yellowish-brown very friable loamy sand to mottled brown sandy clay loam. The underlying material is light brownish-grey and fine gravel and extends to a very dense compacted fine sand layer at approximately 6.0 m below the surface.

Saturated lateral hydraulic conductivity was determined by the auger hole method with the auger hole extending to 0.9 m during the spring of 1986. The results ranged from 30 mm/h to 70 mm/h. In October 1986 further hydraulic conductivity investigations were made using the velocity head permeameter (Merva, 1987) in five backhoe excavations. The velocity head permeameter results ranged from 20 mm/h to 460 mm/h with the 460 mm/h being located in a gravel layer just below drain pipe depth.

The topography of the site allowed subdivision of the St Johns site into five water table management zones, A through E, in which the surface variance within a zone did not exceed 0.30 m. The surface elevation of the zones (from an arbitrary datum) vary from 30.14 m to 30.45 m for zone A, 29.90 m to 30.14 m for zone B, 29.59 m to 29.90 m for Zone C and 29.29 m to 29.59 m for Zones D and E. The subsurface drainage / subirrigation system consists of 102 mm inside diameter (ID) corrugated plastic tubing laterals discharging into corrugated plastic submains and mains ranging in size from 127 mm through 305 mm ID. The system was installed August 11-13, 1986 by members of the Michigan Land

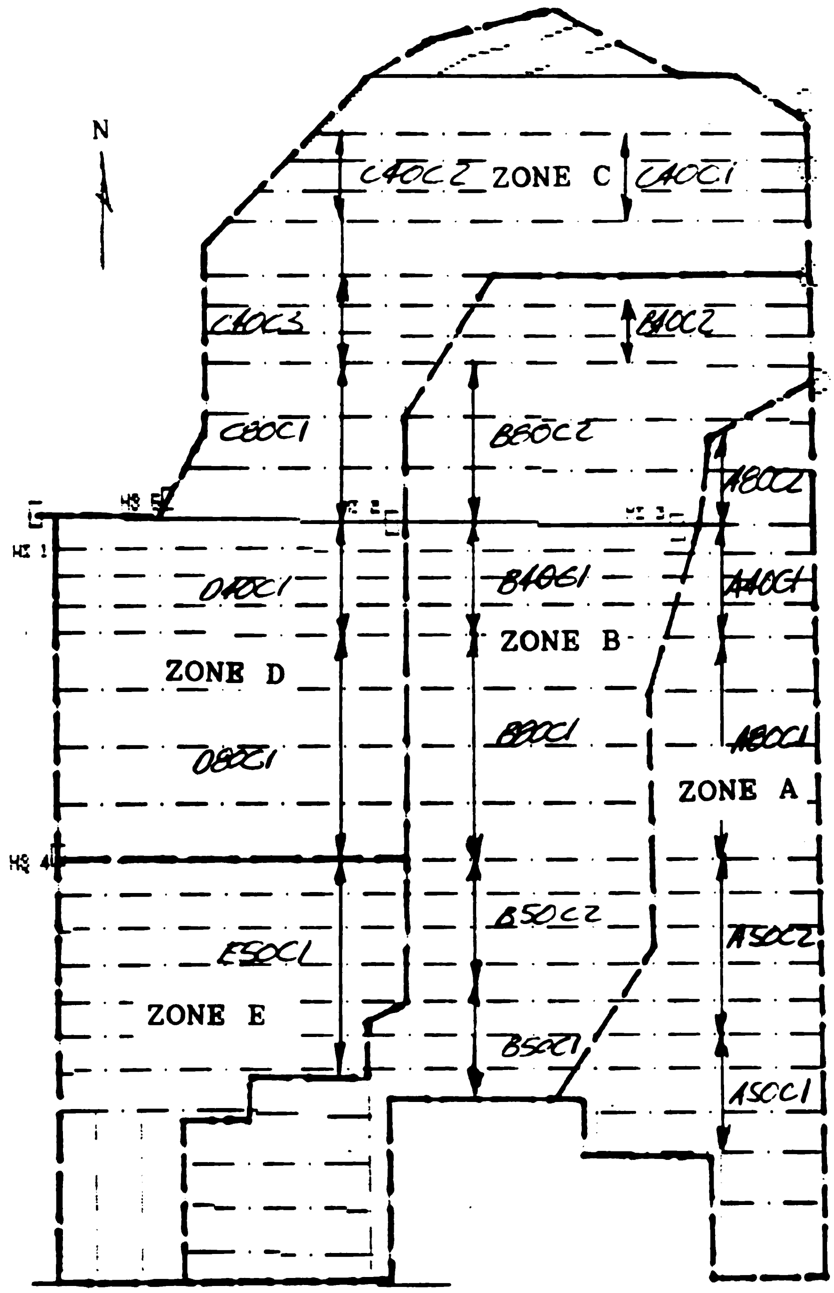


Figure 5. St. Johns site water management zones (A through E), subsurface drainage pipe layout (lateral spacing 12, 17, 24 m) and treatments within each zone (for example A50C1).

Improvement Contractors Association. The submains and mains were installed by a trenching machine. The laterals were installed by drainage plows. The laterals are at 12, 17 and 24 m spacing as shown by Figure 5. The depths to the lateral inverts vary from 1.1 m to 1.4 m below the ground surface. The installed system provides up to 18 irregularly shaped treatment plots that vary in size.

Meteorological Data:

At the Bannister site during the 1986 and 1987 growing season and at the St. Johns site during the 1988 growing season, the minimum daily meteorological data set defined by the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) program of the United States Agency for International Development (Jones, 1984) was collected throughout the growing season. The data collected consists of the date, total daily solar irradiance, minimum daily air temperature, maximum daily air temperature, mean daily air temperature and total daily precipitation. A pyranometer at each site was used to sense solar irradiance. Air temperature data was measured with a linear thermistor at each site. Daily precipitation was measured with a tipping bucket rain gauge and the hourly precipitation was from a bubbler system rain gauge using the technique reported by Goebel (1986).

For the St. Johns site 1987 growing season, the maximum and minimum air temperatures and daily precipitation data collected at the National Weather Service Cooperative

Observer Station Index No. 20-7280-9 (Section 9, T.7 N., R.2 W.) were used for subsequent analyses. That station is 6 km NE of the St. Johns site.

Agronomic Data:

The agronomic data collected at each site included seeding date, emergence date, harvest date, seed cultivar identification, population seeded, population after emergence, nutrients and pesticides applied and crop yield.

At the end of each growing season each treatment plot was harvested and the harvested weight measured using a weigh wagon. The harvest moisture content was determined using an electronic moisture meter (Hydroprobe Model 503 DR manufactured by CPN Corp., Pacheco, CA). During the harvest operation, the boundaries of each yield plot were flagged and field measurements made following harvest to determine plot area.

The relative yield was calculated by dividing the measured yield (corrected to 15.5% moisture for corn and 13% moisture for soybeans) by the management goal for the crops (12,120 kg/ha for corn and 4,300 kg/ha for soybeans).

System Operation Data:

A record of the operation of each water table management system was maintained by recording the dates the pumps were started or stopped and recording any change in the setting of water table controls during the growing season. The electrical power required for operation of each system was also recorded. During the 1988 growing season, the rate of irrigation water flow into each water management zone was monitored and recorded.

Ground Water Data:

To meet the research objectives, it is essential the elevation of the water table be closely monitored for each treatment plot throughout the growing season. The water table is defined as the upper surface of ground water or that level in the soil where the water is at atmospheric pressure (Soil Sci. Soc. Am. 1978). To achieve that capability, observation wells were installed at the approximate locations shown by Figures 6 and 7. For each treatment plot, a well was installed midway between the laterals approximately in the center of the plot and another 1 m from an adjacent lateral. In many of the plots a third observation well was installed midway between the laterals approximately 20 m from the upper end of the plot.

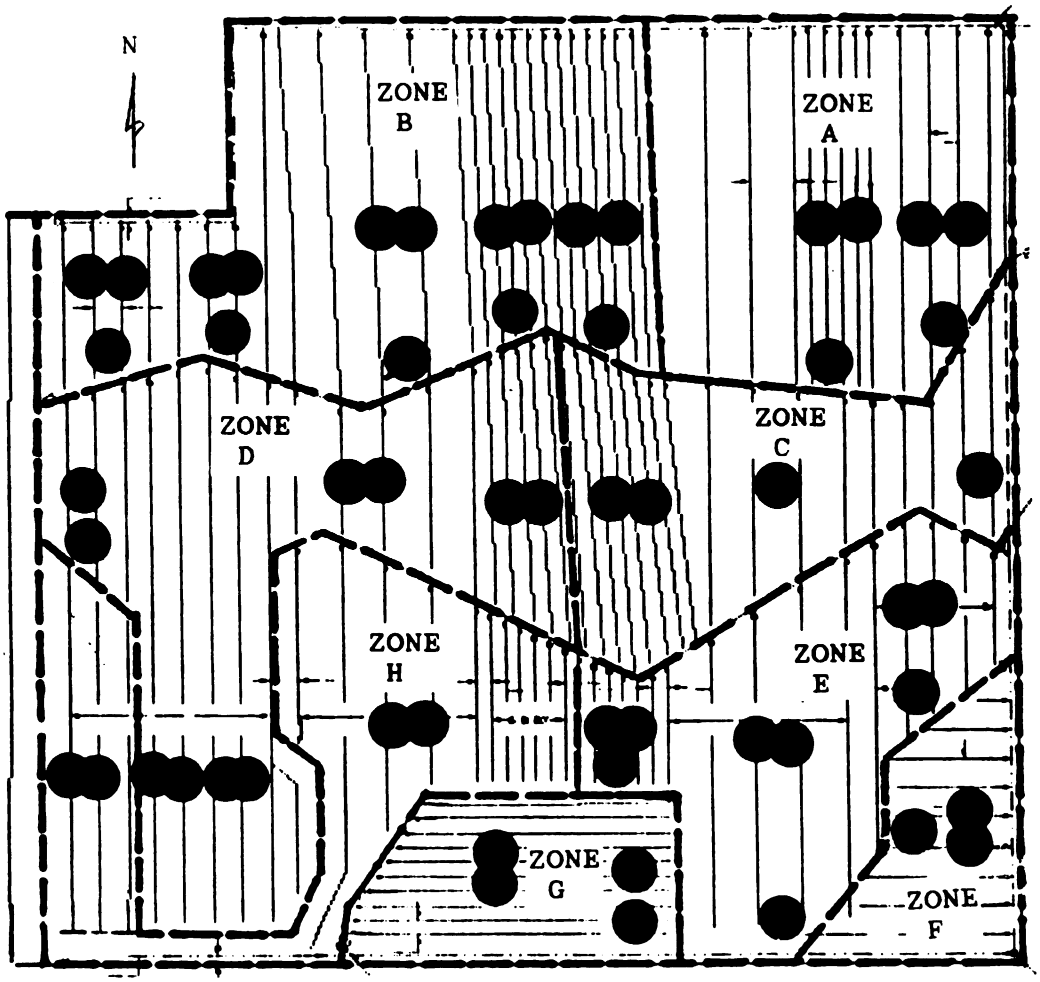


Figure 6. Bannister site well locations. Groups of three within a set of laterals equally spaced are located 1 m from the lateral, midway between the laterals and at the upper end of the water management zone, midway between laterals.

For the 1986 growing season, all wells were constructed of 1.5 m length, 19 mm diameter polyvinyl-chloride (PVC) pipe with holes drilled throughout their length. The wells were wrapped with a thin spun fiberglass material to prevent soil movement into the well. The wells were fabricated so that the top 0.40 m could be removed to allow field operations. The wells were installed using a 100 mm diameter bucket soil auger and backfilled with soil from the site. After the 1986 growing season field operations were completed, the PVC wells were replaced with 1.5 m length, 19 mm diameter galvanized steel electrical conduit with holes drilled throughout the length and with a fiberglass material wrap as above. Using galvanized steel greatly assisted in locating the observation wells using a magnetic locator device when the top portion of the wells were removed. The observation wells at the St. Johns site are galvanized steel with dimensions similar to the Bannister site wells. The St. Johns site wells were installed prior to seeding for the 1987 growing season.

The value of open auger holes for the measurement of water table position has been questioned by many researchers (for example Hinson et al. 1970; Anonymous, 1978; Bouma et al. 1980). Further, potential errors in water table measurements due to soil inhomogeneity and anisotropy using water table wells are discussed by Merva and Fausey (1986). However for structured clays, Armstrong (1983) shows that water table differences between sites can be detected with confidence using open auger hole techniques. Also, earlier work by Merva and Fausey (1984) indicates that the small diameter (19 mm) casing used at the Bannister site is sufficiently responsive to water table fluctuation to

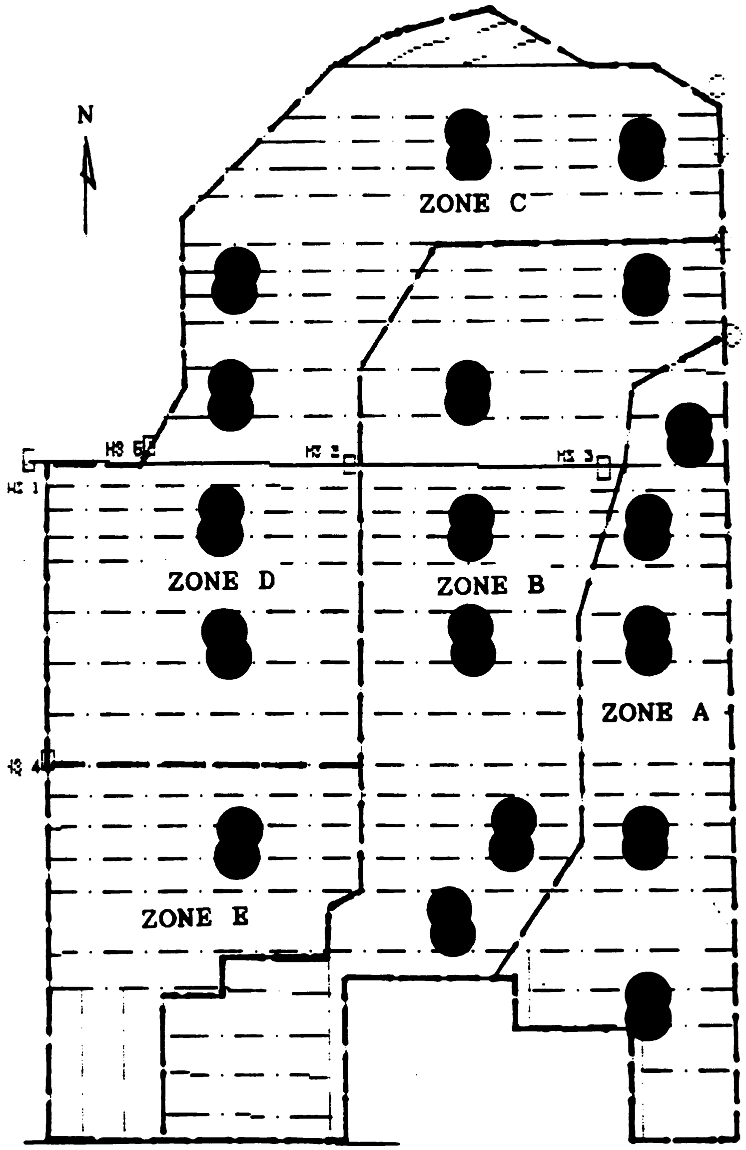


Figure 7. St. Johns site well locations. Groups of two within a set of laterals equally spaced are located at 1 m from the lateral, midway between the laterals and at the upper end of the water management zone, midway between laterals.

provide an accurate hourly measurement of the water table location.

At both sites the data acquisition system for the observation wells is a modification of the bubbler system described by Goebel and Merva (1985) and Goebel (1986). The modification consists of adding a switching mechanism to allow the number of wells to be increased from a maximum of 8 to a maximum of 64. All components of the data acquisition system are off-the-shelf items and are relatively inexpensive. The pressure transducers used at Bannister during the 1986 growing season had a range of 0 to 700 mm of water with an accuracy of 0.4 mm. To improve the range of water table rise and fall that could be monitored during the 1987 growing season, the 1986 growing season Bannister site pressure transducers were replaced with pressure transducers having a range of 0 to 1400 mm of water and an accuracy of 0.7 mm. The pressure transducers at the St. Johns site had a range of 0 to 1400 mm and an accuracy of 0.7 mm for the 1987 and 1988 growing seasons.

The power source for operation of the data acquisition hardware consists of two deep cycle marine type 12 volt batteries. At the start of the 1988 growing season, commercial electrical service was installed at the St. Johns site. The commercial electrical service was used to charge the system 12 volt batteries by a commercial battery charger. Using batteries to power the system allows the system to operate when the commercial electrical service fails or is interrupted.

The water table data acquisition system was made operational following seeding and cultivating operations and maintained in an operational mode until near harvest time. For the 1986 growing season, data acquisition at the Bannister site began June 9 and ended October 27. For the 1987 growing season, data acquisition at the Bannister site began July 2 and ended September 16 and at the St. Johns site began July 1 and ended September 18. For 1988, data acquisition at the St. Johns site began June 20 and ended October 27.

Operation of the observation well / data acquisition system requires one time installation of the observation wells and data acquisition components, removal and replacement of observation well tops for each field operation (tillage, seeding, cultivating and harvesting), a one time determination of observation well top elevations, periodic blow tube readings to calibrate the wells and to provide a check on the data acquisition results, and periodic replacement of the nitrogen supply tank and system batteries. A 6,500 l nitrogen supply tank lasts approximately one month and one of the two 12 v batteries must be replaced with a fully charged battery on a 10 to 14 day schedule.

The output from the data acquisition system consists of well identification, date, time and digital representation of the pressure transducer for each reading. These data were automatically dumped to a cassette tape. The cassettes were replaced approximately weekly. The data on cassettes is transferred to an IBM compatible computer in the office for further transformation and analysis.

Observation Well Data Analysis:

The observation wells and data acquisition systems at the two sites were used to monitor, on an hourly basis, the water table elevation in each treatment plot. The resultant data were then used to evaluate water table response to precipitation events, water table control changes, subirrigation pump startup and shutdown, crop use effects on water table elevation on hourly, daily, weekly, monthly and seasonal time basis for variable lateral spacings and water table management strategies. In addition, hourly water table elevation is an output variable provided by the computer simulation model DRAINMOD (Skaggs, 1978) and thus is useful for model verification and/or calibration.

For analysis the observation well data were transformed as follows:

1. Each well was identified by a code consisting of 6 characters. The first character is always a 'W' for well. The second character designates the water management zone location ('A' to 'H' for Bannister, 'A' to 'E' for St. Johns). Character 3 is for lateral spacing (2, 4 or 6 for 6, 12 and 18 m respectively - Bannister; 4, 5 or 8 for 12, 16 and 24 m respectively -St. Johns). The fourth character represents the location of the well within the plot - M' for Midpoint between laterals, 'L' for 1 m from Lateral and 'E' for midpoint between laterals at End of the plot. The last character is a number used to differentiate between wells within a plot that would otherwise have the same designation.

2. The time was transformed from hour:minute:second to hour and decimal hour.

3. The date was converted from month, day and year to day of year and decimal fraction of the day.

4. The numeric representations of pressure transducer voltage output were correlated with the blow tube

reading elevations for each observation. Only wells with a coefficient of determination (r^2) equal to or greater than 0.80 were used for subsequent analysis. For those wells the regression equation was used to convert the observations from a numeric representation of voltage to a water table elevation.

The hourly water table elevations were averaged for the months of July and August and for the growing season at each observation well location (jwtd, awtd and swtd). The resulting means were then used to 1) calculate the vertical distance above and below the mean water table elevation for each hourly water table observation at each observation well location and 2) calculate the mean water table depth within the zone by subtracting the mean water table elevation from the average surface elevation of the zone. The hourly vertical distance and time above and below the mean water table elevation was accumulated by day, week, month and growing season for each treatment, each crop and each season for both sites. The accumulated time above and below the mean water table elevation was then used to calculate the percent time the water table was above and below the mean water table elevation for each treatment for the months of July and August and the growing season (jtimea, atimea, stimea, jtimeb, atimeb and stimeb). The accumulated time and accumulated distance the water table was above the mean water table elevation was used to calculate a water table fluctuation wet stress index and water table fluctuation dry stress index for July, August and the growing season for each treatment (jwfi,awfi,swfi,jdfi,adfi and sdfi) in accordance with the following equations:

$$\underline{x}wfi = \underline{x}d_a * \underline{x}t_a / \underline{x}t_t \qquad [1]$$

$$\underline{x}dfi = \underline{x}d_b * \underline{x}t_b / \underline{x}t_t \qquad [2]$$

where

$\underline{x}$ =	'j' for July, 'a' for August and 's' for growing season
wfi =	water table fluctuation wet stress index
dfi =	water table fluctuation dry stress index
d_a =	accumulated vertical distance the water table is above the mean water table elevation during July, August or growing season
t_a =	accumulated time the water table is above the mean water table elevation during July, August or growing season
t_t =	accumulated time the water table is above or below the mean water table elevation during July, August or growing season
d_b =	accumulated vertical distance the water table is below the mean water table elevation during July, August or growing season
t_b =	accumulated time the water table is below the mean water table elevation during July, August or season

The water table fluctuation indices quantify both the extent and duration of the water table fluctuation from the mean water table elevation for the water table data available. By including division by t_t in the calculation of wfi and dfi, a comparison of the indices by treatment has meaning even though the period of water table data record may differ slightly between treatments.

Statistical Analyses:

To investigate relationships between yield, the dependent variable, and the independent water table variables, the following linear regression analyses were performed:

I. Y = B0 + B1 * X

A. Y = relative yield, %
X = mean water table depth for the growing season, m

B. Y = relative yield, %
X = percent time below the mean water table elevation for the growing season, %

C. Y = relative yield, %
X = percent time above the mean water table elevation for the growing season, %

D. Y = relative yield, %
X = water table fluctuation dry stress index for the growing season, m*h/h

E. Y = relative yield, %
X = water table fluctuation wet stress index for the growing season, m*h/h

II. Y = B0 + B1 * X

A. Y = relative yield, %
X = mean water table depth for July, m

B. Y = relative yield, %
X = percent time below the mean water table elevation for July, %

C. Y = relative yield, %
X = percent time above the mean water table elevation for July, %

D. Y = relative yield, %
X = water table fluctuation dry stress index for July, m*h/h

E. Y = relative yield, %
X = water table fluctuation wet stress index for July, m*h/h

III. Y = B0 + B1 * X

A. Y = relative yield, %
X = mean water table depth for August, m

B. Y = relative yield, %
X = percent time below the mean water table elevation for August, %

C. Y = relative yield, %
X = percent time above the mean water table elevation for August, %

D. Y = relative yield, %
X = water table fluctuation dry stress index for August, m*h/h

E. Y = relative yield, %
X = water table fluctuation wet stress index for August, m*h/h

Recognizing the water table fluctuation effect is likely to be influenced by a combination of distance and time above and below mean water table elevation as well as the stage of plant development, multiple linear regression analyses using the forward stepping procedure were made on the following data sets:

IV. Y = B0 + B1 * X1 + B2 * X2

A. Y = relative yield, %
X1 = mean water table depth for the season, m
X2 = percent time below the mean water table elevation for the season, %

B. Y = relative yield, %
X1 = mean water table depth for the season, m
X2 = percent time above the mean water table elevation for the season, %

C. Y = relative yield, %
X1 = mean water table depth for the season, m
X2 = water table fluctuation dry stress index for the season, m*h/h

D. Y = relative yield, %
X1 = mean water table depth for the season, m
X2 = water table fluctuation wet stress index for the season, m*h/h

E. Y = relative yield, %
X1 = mean water table depth during July, m
X2 = percent time below the mean water table elevation during July, %

F. Y = relative yield, %
X1 = mean water table depth during July, m
X2 = percent time above the mean water table elevation during July, %

G. Y = relative yield, %
X1 = mean water table depth for July, m
X2 = water table fluctuation dry stress index for July, m*h/h

H. Y = relative yield, %
X1 = mean water table depth for July, m
X2 = water table fluctuation wet stress index for July, m*h/h

I. Y = relative yield, %
X1 = mean water table depth during August, m
X2 = percent time below the mean water table elevation during August, %

J. Y = relative yield, %
X1 = mean water table depth during August, m
X2 = percent time above the mean water table elevation during August, %

K. Y = relative yield, %

X1 = mean water table depth for August, m
X2 = water table fluctuation dry stress index for August, m*h/h

L. Y = relative yield, %
X1 = mean water table depth for August, m
X2 = water table fluctuation wet stress index for August, m*h/h

To investigate the effect of water table management system physical proportions, the relative yield data were correlated with water management zone and lateral spacing for each site and each growing season as follows:

V. Y = B0 + B1 * X

A. Y = relative yield, %
X = lateral spacing, m

B. Y = relative yield, %
X = water management zone

Results

Meteorological Data:

The meteorological data collection efforts for the two sites provided: accumulated daily rainfall data (Figures 8 and 9); daily low, high (Figures 10 through 13) and mean air temperature; daily integrated solar irradiance (Figures 14 and 15); and accumulated degree days (Figures 16 and 17). System failure at St. Johns prevented obtaining good data for the latter part of the 1988 growing season.

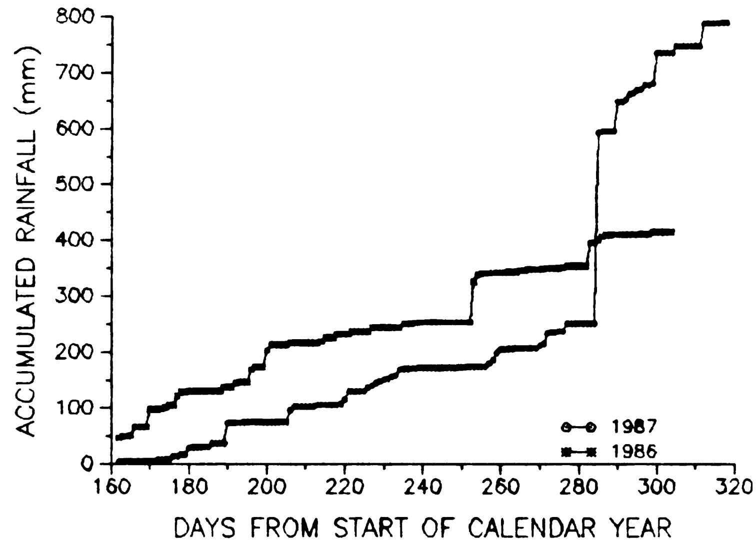


Figure 8. Bannister site accumulated rainfall for 1986 and 1987 growing seasons in mm.

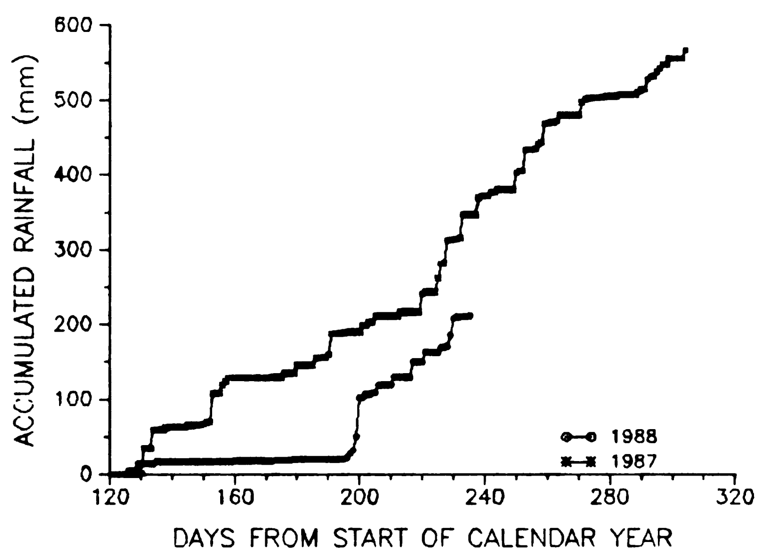


Figure 9. St. Johns site accumulated rainfall for 1987 and 1988 growing seasons in mm.

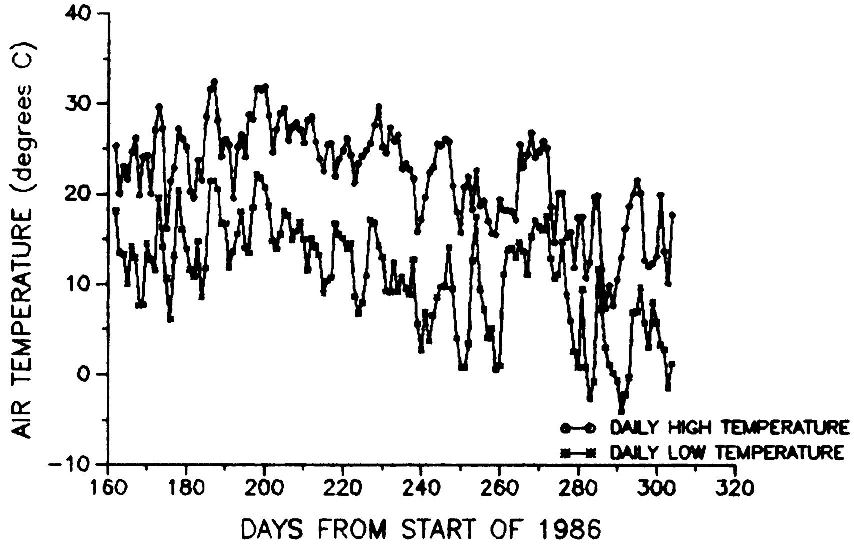


Figure 10. Bannister site 1986 growing season daily low and high air temperatures in degrees C.

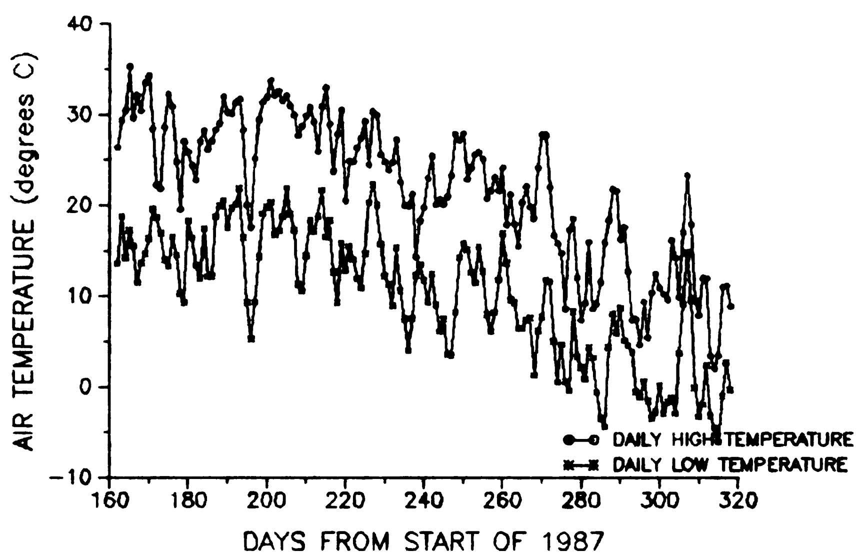


Figure 11. Bannister site 1987 growing season daily low and high air temperatures in degrees C.

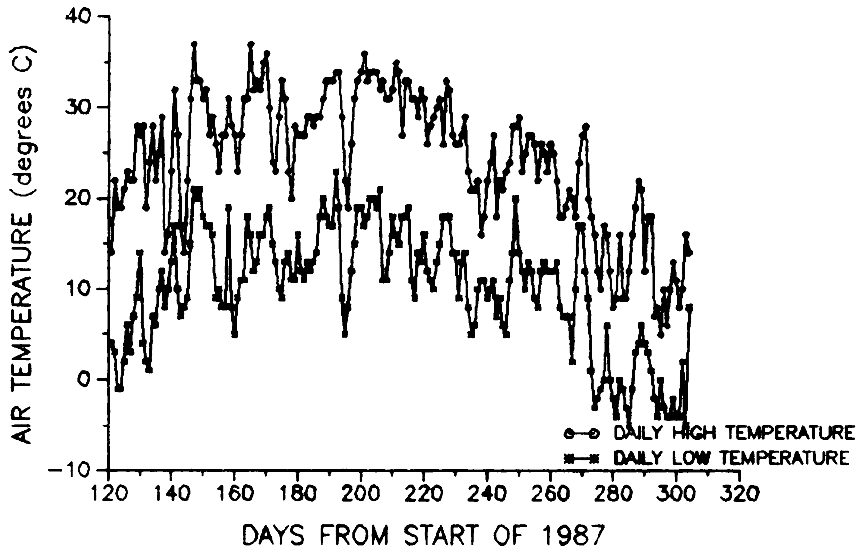


Figure 12. St. Johns site 1987 growing season daily low and high air temperatures in degrees C.

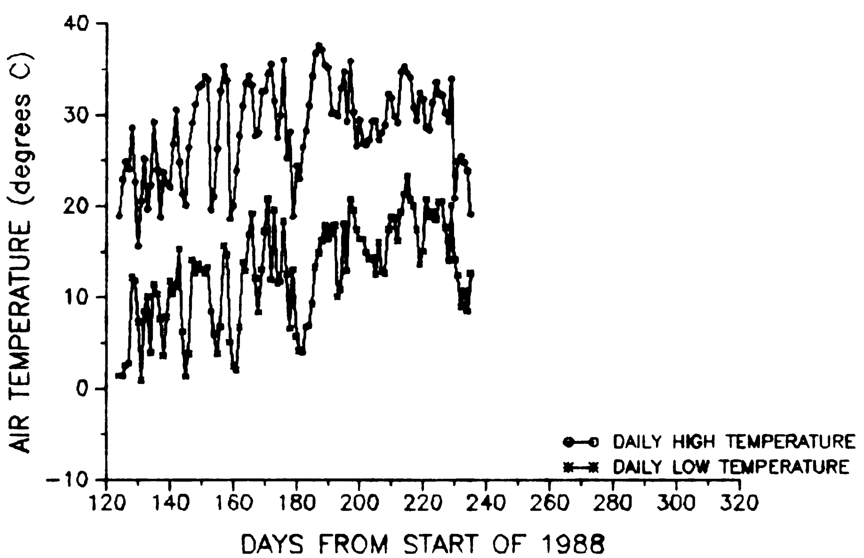


Figure 13. St. Johns site 1988 growing season daily low and high air temperatures in degrees C.

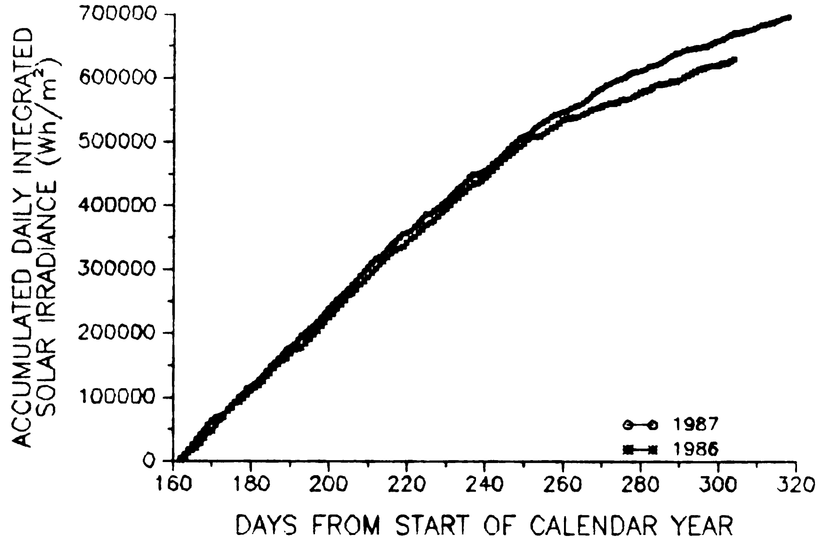


Figure 14. Bannister site accumulated solar irradiance for 1986 and 1987 growing season in W'h/m^2.

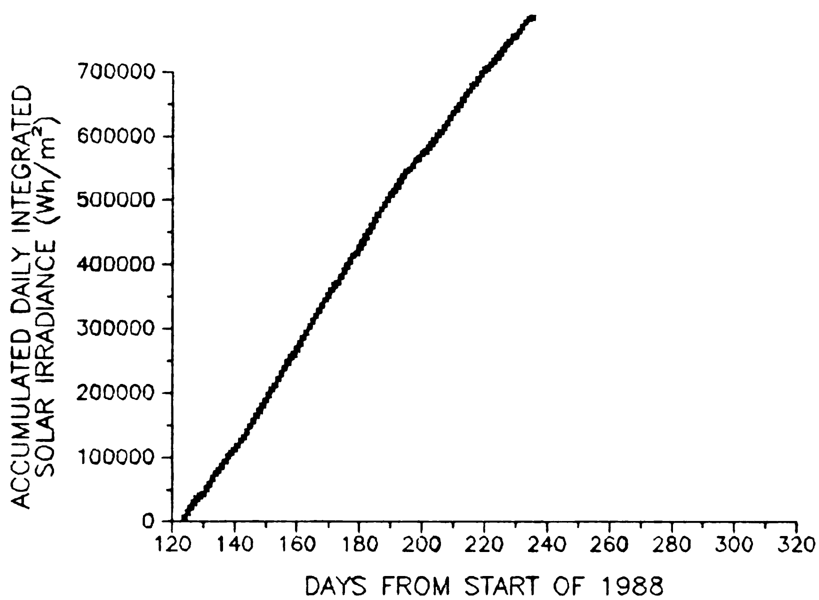


Figure 15. St. Johns site accumulated solar irradiance for 1988 growing season in W'h/m^2.

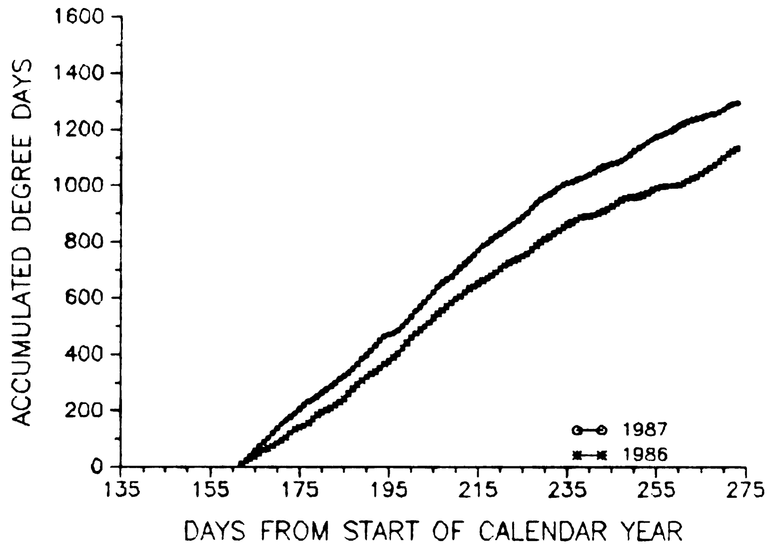


Figure 16. Bannister site accumulated heat units in degree C-days for 1986 and 1987 growing seasons.

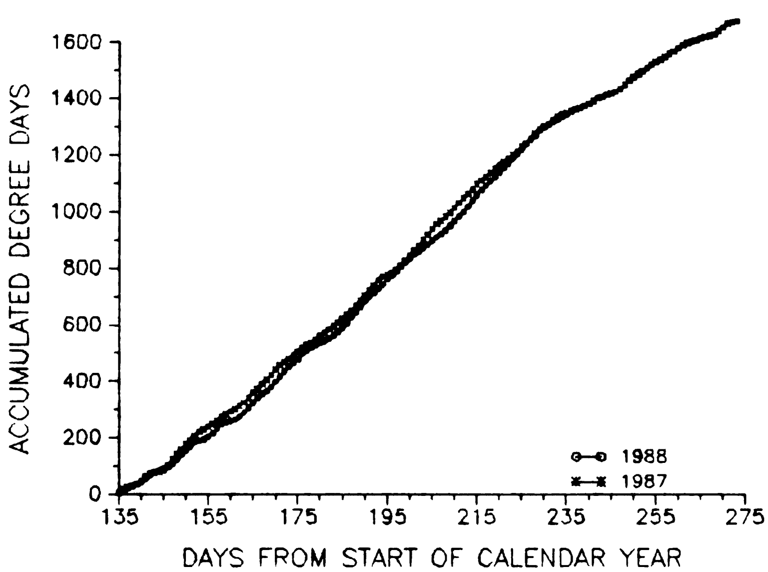


Figure 17. St. Johns accumulated heat units in degree C-days for 1987 and 1988 growing seasons.

Agronomic Data:

The agronomic data for the Bannister site is presented in Tables 2 and 3.

Table 2. Bannister site 1986 growing season agronomic data summary.

1986 CORN (Great Lakes 579)		1986 SOYBEANS (Hoytville / Great Lakes 2634)		
WT MGMT ZONE	EMERG'D POPUL'N plants/ha	WT MGMT ZONE	VARIETY	EMERG'D POPUL'N plants/ha
A	65460	A	Hoyt	871800
			GL 2634	551600
B	65460	B	Hoyt	844700
			GL 2634	738800
C	66760	C	Hoyt	
			GL 2634	610700
D	67200	D	Hoyt	
			GL 2634	568800
E	60850	E	Hoyt	651000
			GL 2634	331200
F		F	Hoyt	572600
			GL 2634	325100
H	66340	H	Hoyt	562700
			GL 2634	402600

CORN		SOYBEANS	Hoyt	GL 2634
DATE SEEDED:	05/06/86	DATE SEEDED:	05/29/86	05/29/86
DATE OF EMERGENCE:	05/12/86	DATE OF EMERGENCE:	06/05/86	06/07/86
DATE OF HARVEST:	11/10/86	DATE OF HARVEST:	10/06/86	10/06/86

FERTILIZER (corn):
55 kg/ha Potash
31 L/ha 28% Nitrogen
37 kg/ha 18-40-0 (starter)
112 kg/ha 28% Nitrogen (sidedress)

FERTILIZER (soybeans):
55 kg/ha Potash
31 L/ha 28% Nitrogen
28 kg/ha 12.5-11-11 (starter)

PESTICIDES (corn):
0.8 L/ha Lasso
0.3 kg/ha Atrax 90

PESTICIDES (soybeans):
0.8 L/ha Lasso
0.1 kg/ha Sencor

Table 3. Bannister site 1987 growing season agronomic data summary table.

1987 CORN (Great Lakes 579)		1987 SOYBEANS (Hoytville/Great Lakes 2634)	
WT MGMT ZONE	EMERG'D POPUL'N plants/ha	WT MGMT ZONE	EMERG'D POPUL'N plants/ha
A	61240	A	479300
B	61490	B	486500
C	58900	C	501600
D	64080	D	483200
E	65670	E	411500
H	66040		
DATE SEEDED:	05/08/87	DATE SEEDED:	05/23/87
DATE OF EMERGENCE:	05/18/87	DATE OF EMERGENCE:	
DATE OF TASSELING:	07/09/87	DATE OF FLOWERING:	07/16/87
DATE OF HARVEST:		DATE OF HARVEST:	
FERTILIZER: 55 kg/ha Potash; 31 L/ha 28% Nitrogen; 37 kg/ha 18-46-0 (starter); 37 kg/ha Anhydrous (sidedress)		FERTILIZER: 55 kg/ha Potash	
PESTICIDES: 0.8 L/ha Lasso; 0.3 kg/ha Atrax 90		PESTICIDES: 0.8 L/ha Lasso; 0.1 kg/ha Sencor	

The agronomic data for the St. Johns site is presented in Tables 4 and 5.

Table 4. St. Johns site 1987 growing season agronomic data summary table.

1987 CORN (Pioneer 3475)		1987 SOYBEANS (Pioneer 9771)	
WT MGMT ZONE	EMERG'D POPUL'N plants/ha	WT MGMT ZONE	EMERG'D POPUL'N plants/ha
A	73550	A	417200
B	68750	B	399600
C	71532	C	366500
D	70158	D	350800
E	71075	E	402000
DATE SEEDED:	04/28/87	DATE SEEDED:	05/20/87
DATE OF EMERGENCE:	05/08/87	DATE OF EMERGENCE:	05/28/87
DATE OF TASSELING:	07/09/87	DATE OF FLOWERING:	07/16/87
DATE OF HARVEST:	10/27/87	DATE OF HARVEST:	10/16/87
FERTILIZER:		FERTILIZER:	
55 kg/ha 0-0-60	(preplant)	55 kg/ha 0-0-60	(preplant)
49 kg/ha 7-28-18	(04/28/87)	18 kg/ha 9-23-30	(05/20/87)
1 kg/ha sulfer	(04/28/87)		
61 L/ha 28% N	(05/12/87)		
33 kg/ha 83% Anhydrous	(06/09/87)		
PESTICIDES:		PESTICIDES:	
0.2 L/ha Lorox +		0.3 kg/ha Aatrex	
0.3 L/ha Dual		0.4 L/ha Dual	

Table 5. St. Johns site 1988 growing season agronomic data summary table.

1988 CORN (Pioneer 3475)		1988 SOYBEANS (Pioneer 9271)	
WT MGMT ZONE	EMERG'D POPUL'N plants/ha	WT MGMT ZONE	EMERG'D POPUL'N plants/ha
A	71200	A	310000
B	68900	B	292000
C	66930	C	258100
D	68680	D	
E	101490	E	
DATE SEEDED:	04/30/88	DATE SEEDED:	05/17/88
DATE OF EMERGENCE:	05/11/88	DATE OF EMERGENCE:	05/24/88
DATE OF TASSELING:	07/09/88	DATE OF FLOWERING:	07/20/88
DATE OF HARVEST:	10/27/88	DATE OF HARVEST:	11/17/88
FERTILIZER:		FERTILIZER:	
37 kg/ha Urea	(preplant)	37 kg/ha 7-14-80	(05/17/88)
37 kg/ha Potash	(preplant)		
37 kg/ha 25-7-20	(04/30/88)		
33 kg/ha NH3	(supplemental)		
PESTICIDES:		PESTICIDES:	
0.3 L/ha Aatrix		0.8 L/ha Lasso	(Pre-emer.)
0.8 L/ha Lasso		0.2 L/ha Lorax +	(Pre-emer.)
0.4 L/ha Buctril		0.2 L/ha Blazer	(Post-emer.)
		0.4 L/ha Basagran	(Post-emer.)
		0.4 L/ha Crop Oil	(Post-emer.)

The corn and soybean yields obtained for the Bannister and St. Johns sites are tabulated by treatment as a part of Table 9.

System Operation Data:

Operating the water table management systems at each site consisted of starting and stopping the irrigation supply pumps and adjusting the water table control for each water table management zone to set the system in subsurface drainage or subirrigation and to raise and lower the water table within each zone. Tables 6 and 7 are summaries of those operations for each site. The elevations refer to an arbitrary datum of 30.48 m set as a temporary benchmark at both the St. Johns and Bannister sites.

Ground Water Data:

For the Bannister site, during the 1986 growing season, water table measurements began June 9, 1986 and ended October 27, 1986. Water table measurements at 55 locations produced 29,965 water elevation observations during that time period. During the 1987 growing season the water table measurements began July 2, 1987 and continued through September 23, 1987 and resulted in 29,284 water table elevation observations. The output from each observation

Table 6. Bannister site water table management system operation summary.

1986 GROWING SEASON:

DATE	ZONE A B	ZONE C	ZONE D	ZONE E&H	ZONE
		ELEVATION OF WEIR (m)			
05/01	Dr.[1]	Dr.[1]	Dr.[1]	Dr.[1]	Dr.[1]
06/01	Dr.[1]	29.79	30.08	30.22	30.51
07/05	Dr.[1]	29.89	29.93	30.07	30.41
08/01	Dr.[1]	30.09	29.93	30.07	30.31
09/07	Dr.[1]	29.99	29.93	30.07	30.61
10/01	Dr.[1]	Dr.[1]	Dr.[1]	Dr.[1]	Dr.[1]

PUMP SCHEDULE: start 07/04 stop 09/06

1987 GROWING SEASON:

DATE	ZONE A B	ZONE C	ZONE D	ZONE E&H	ZONE F	ZONE G	ZONE
			ELEVATION OF WEIR (m)				
05/01	Dr.[1]	Dr.[1]	Dr.[1]	Dr.[1]	Dr.[1]	Dr.[1]	Dr.[1]
06/12	Dr.[1]	28.17	28.90	29.00	29.90	29.36	29.62
06/15	Dr.[1]	29.72	29.78	29.83	30.54	30.46	30.98
06/22	Dr.[1]	29.70	29.78	29.80	30.69	30.15	30.62
06/26	Dr.[1]	29.69	29.78	29.86	30.69	30.43	30.46
07/07	Dr.[1]	29.69	29.78	29.86	30.69	29.94	
08/18	Dr.[1]	29.42	29.18		30.30	30.14	30.17
08/20	Dr.[1]	Dr.[1]	Dr.[1]	Dr.[1]	Dr.[1]	Dr.[1]	Dr.[1]

PUMP SCHEDULE: start 06/12 stop 07/01
start 07/02 stop 08/20

[1] Water table control set for subsurface drainage.

Table 7. St. Johns site water table management system operation summary.

1987 GROWING SEASON:

DATE	ZONE A B	ZONE C	ZONE D	ZONE E	ZONE
	ELEVATION OF WEIR (m)				
05/26	Dr.1	Dr.[1]	Dr.[1]	Dr.[1]	Dr.[1]
05/27	29.82	29.69	29.66	Dr.[1]	29.69
08/27	Dr.[1]	Dr.[1]	Dr.[1]	Dr.[1]	Dr.[1]

PUMP SCHEDULE: start 06/22 stop 08/27

1988 GROWING SEASON:

DATE	ZONE A B	ZONE C	ZONE D	ZONE E	ZONE
	ELEVATION OF WEIR (m)				
03/28	Dr.[1]	Dr.[1]	Dr.[1]	Dr.[1]	Dr.[1]
03/29	29.82	29.69	29.66	Dr.[1]	29.69
09/15	Dr.[1]	Dr.[1]	Dr.[1]	Dr.[1]	Dr.[1]

PUMP SCHEDULE: start 05/24 stop 09/15

[1] Water table control set for subsurface drainage.

well was compared to field measured depths to the water table by regression analyses. The regression coefficient of determination (r^2) exceeded 0.80 for 17 observation wells in 1986 and 13 observation wells in 1987 (see Table 8). For subsequent analyses the number of wells was further reduced to one well per treatment. The preferred well was a well located midway between laterals with the highest coefficient of determination (r^2). Thus, for Bannister, the number of groundwater observations used for analyses reduced to 9,085 observations from 11 wells for 1986 and 4,001 observations from 7 wells for 1987.

At the St. Johns site, 7 of 36 observation wells produced regression coefficients of determination (r^2) greater than 0.80. Of these, 6 of 36 observation wells providing 9,085 useful hourly water table elevation observations (beginning July 1, 1987 and ending September 18, 1987), which were used for subsequent analyses. During the 1988 growing season, water table elevation monitoring began June 20, 1988 and continued until October 27, 1988 producing 14,032 observations from 7 observation wells all of which were used for subsequent analyses.

The observation wells used for subsequent analyses are listed in Table 8.

Table 8. Regression equations for ground water observation wells used at Bannister and St. Johns sites.

WELL ID	REGRESSION EQUATION	r2	n
Bannister, 1986			
WA4M1	y=28.22+.00680*x	0.936	3
WB2L2	y=28.63+.00447*x	0.975	3
WB2M2	y=29.00+.00282*x	0.999	4
WB4L1	y=28.99+.00295*x	1.000	3
WB4E1	y=29.11+.00351*x	0.899	3
WB4M2	y=29.01+.00278*x	0.982	4
WB6L1	y=29.17+.00453*x	0.983	3
WC2L1	y=29.25+.00334*x	0.955	3
WC6M1	y=29.17+.00356*x	0.996	3
WD2L1	y=29.28+.00298*x	0.883	4
WD6L1	y=29.22+.00282*x	0.880	4
WD6M1	y=29.38+.00214*x	0.973	3
WE2L1	y=30.02+.00294*x	0.944	5
WE2M1	y=29.65+.00234*x	0.937	3
WG2L1	y=29.97+.00265*x	0.933	3
WG2M1	y=29.96+.00270*x	0.991	4
WH4M2	y=29.43+.00220*x	0.984	4
Bannister, 1987			
WB4L1	y=27.98+.00628*x	1.000	4
WC2L1	y=28.30+.00375*x	0.978	5
WC2M1	y=28.55+.00355*x	0.967	5
WD2L1	y=28.58+.00434*x	0.814	5
WD4E1	y=29.09+.00193*x	0.956	5
WD6L1	y=28.89+.00309*x	0.838	6
WD6M1	y=28.43+.00615*x	0.918	3
WE2M1	y=29.13+.00325*x	0.979	3
WE4L1	y=28.75+.00354*x	0.801	5
WE4M1	y=29.11+.00399*x	0.976	5
WE4E1	y=29.32+.00327*x	0.982	4
WF4M1	y=28.54+.00402*x	0.972	5
WH4M2	y=28.78+.00405*x	0.997	3
St. Johns, 1987			
WB4L2	y=27.93+.00797*x	0.955	3
WB4M2	y=27.48+.00765*x	1.000	3
WC4L1	y=27.71+.00514*x	0.957	3
WC4M1	y=27.94+.00636*x	0.845	6
WC4M2	y=27.94+.00636*x	0.845	5
WC4M3	y=28.14+.00642*x	0.972	5
WD8L1	y=28.57+.00144*x	0.851	3
St. Johns, 1988			
WA5L1	y=28.89+.00542*x	0.909	3
WA5M1	y=28.47+.00454*x	0.824	3
WA8M1	y=28.59+.00475*x	0.988	4
WB5L1	y=28.42+.00516*x	0.943	4
WC8M1	y=28.41+.00532*x	0.964	3
WC4M3	y=28.21+.00425*x	0.849	4
WD8L1	y=28.54+.00551*x	0.968	3

where y = water table elevation
x = pressure transducer readout converted to digital
r2 = correlation coefficient squared
n = number of observations

A summary of the blow tube measured water table elevations and a tabulation of the average relative yield and lateral spacing within each water management zone is provided by

Table 9. For spacings within zones with more than a single treatment, the yields shown are the arithmetic average of the yields. For the 1986 season, the mean water table depths in Table 9 are the average of 6 measured elevations during the time period 6/25/86 through 7/30/86. For 1987 the Bannister mean water table depths are from 7 measurements taken between 7/01/87 and 8/24/87. The 1987 St. Johns mean depths are the average of 6 measurements between 7/14/87 and 8/17/87 and for 1988, 10 readings taken from 6/7/88 to 8/15/88.

For the 1986 growing season at Bannister the maximum water table depth (growing season, July and August) occurred in zone A, the zone without water table control. The least water table depth occurred in zone B, the zone with the water table control set nearest the soil surface. For 1987 automatically collected observation well data for zone A is not available because for most of the season the water table in zone A was below the lower capability of the instrumentation. For the other zones, the mean water table elevation differed from zone to zone. For zones A and B, the blow tube measured water table depths (for observation wells WA4M1 and WB4M2) show a mean water table depth of 1.38 m and 0.51 m.

The results of the analyses of the hourly observation well observations for the Bannister and St. Johns sites are provided by Table 10. Table 10 also provides the relative yields measured for each treatment used in the analyses. The Table 10 treatment codes are provided as a part of Figures 3 and 5. The observation well codes were defined previously in the Observation Well Data Analysis part of the Methodology section of FIELD STUDIES.

Table 9. Summary of yields and blow tube measured water table depths by zone and lateral spacing.

Trt.	Zone	Lateral Spacing	Corn Yield	Soybean Yield	Mean WT Depth	Corn Yield	Soybean Yield	Mean WT Depth
		m	%	%	m	%	%	m
				--xx=86--			--xx=87--	
BxxA20	A	6	85	65	0.95	86	89	1.44
BxxA40	A	12	75	60	0.75	79	80	1.41
BxxA60	A	18	83	60	0.58	68	85	1.23
BxxB20	B	6	86	48	0.53	113	88	0.48
BxxB40	B	12		52	0.54	92		0.60
BxxB60	B	18	83	51		93	78	
BxxC20	C	6	75	63	0.77	86	79	1.06
BxxC40	C	12	79	60	0.38	79	88	
BxxC60	C	18	83	52	0.79	100	93	0.82
BxxD20	D		75	63	0.72	86	80	0.83
BxxD40	D	12	79	63	0.68	85	95	0.95
BxxD60	D	18	68	58	0.74	78	92	0.96
BxxE20	E	6	77		0.77		71	0.73
BxxE40	E	12	63		0.83		89	0.87
BxxE60	E	18	77	55		77	92	
BxxF40	F	12	78	60		83	74	1.58
BxxG20	G	6		58	0.73	69		0.63
BxxH20	H	6	77				71	
BxxH40	H	12	88	71	0.75	80	82	0.67
BxxH60	H	18	84		0.64		92	1.02
				--yy=87--			--yy=88--	
SyyA40	A	12	72	49	0.89	84	52	1.01
SyyA50	A	17	84	45	0.91	97	71	0.90
SyyA80	A	24	68	45	0.98	80	53	1.06
SyyB40	B	12	77	39	1.02	75	65	1.08
SyyB50	B	17	94	42	0.89	99	68	
SyyB80	B	24	80	47	0.90	87	78	0.89
SyyC40	C	12	79	56	1.05	58	55	1.12
SyyC80	C	24	72	66	1.16	49	65	1.12
SyyD40	D	12	81	82	0.92	83	83	0.70
SyyD80	D	24	84	80	0.86	91	80	0.71
SyyE50	E	17	87	72		92	70	

Table 10. Relative yield results by treatment and observation well data analyses results.

TREATMENT ID	OBS WELL ID	CORN REL YIELD % cyield	SOYBEAN REL YIELD % syield	LATERAL SPACING m spacing	SEASON MEAN WT DEPTH m swtd	SEASON TIME BELOW MEAN WT % stimeb	SEASON TIME ABOVE MEAN WT % stimea	SEASON DRY FLUCT INDEX $m^{2}h/h$ sdfi	SEASON WET FLUCT INDEX $m^{2}h/h$ swfi	JULY MEAN WT DEPTH m jwtd	JULY TIME BELOW MEAN WT % jtimeb	JULY TIME ABOVE MEAN WT % jtimea	JULY DRY FLUCT INDEX $m^{2}h/h$ jdfi	JULY WET FLUCT INDEX $m^{2}h/h$ jwfi	AUGUST MEAN WT DEPTH m awtd	AUGUST TIME BELOW MEAN WT % atimeb	AUGUST TIME ABOVE MEAN WT % atimea	AUGUST DRY FLUCT INDEX $m^{2}h/h$ adfi	AUGUST WET FLUCT INDEX $m^{2}h/h$ awfi
Bannister '86																			
A40C1	WA4M1	75	60	12	.81	31	67	37	81	.66	38	57	8.4	12.7	1.02	37	62	7.5	12.5
B20C2	WB2M2	86	48	6	.48	29	68	9	20	.45	33	64	4.3	8.3	.56	60	40	.4	.3
B40C1	WB4M2		52	12	.47	33	66	11	21	.45	35	57	4.8	7.8	.44	39	61	1.7	2.7
B60C1	WB6L1	83	51	18	.45	49	43	19	16	.45	54	34	5.1	3.3	.45	43	56	4.3	5.6
C20C1	WC2L1	75	63	6	.58	58	41	55	39	.69	61	30	10.6	5.2	.37	43	55	4.6	5.7
C60C1	WC6M1	83	52	18	.77	54	44	42	34	.72	54	44	14.5	11.9	.95	57	43	5.8	4.4
D20C1	WD2L1	75	63	6	.61	68	30	31	14	.65	60	38	8.3	5.3	.54	61	38	1.4	.8
D60C1	WD6M1	68	58	18	.72	41	58	27	38	.66	53	39	7.2	5.3	.91	73	19	2.4	.6
E20C1	WE2M1	77		6	.79	63	35	45	25	.83	63	33	14.8	7.9	.90	52	45	4.1	3.6
G20C1	WG2M1		58	6	.77	62	37	52	31	.75	62	35	17.0	9.6	.93	58	13	1.0	.2
H40C1	WH4M2	88	71	12	.81	52	43	19	16	.84	52	46	8.6	7.7	.75	36	64	3.5	6.3
Bannister '87																			
C20C1	WC2M1	86	79	6	1.15	42	57	17	24	.98	31	60	1.3	2.6	1.19	43	56	4.8	6.3
D20C1	WD2L1	86	80	6	.99	47	52	32	35	.73	23	68	1.3	3.8	1.04	54	45	11.0	9.2
D60C1	WD6L1	78	92	18	1.03	61	36	27	16	.82	45	47	2.2	2.3	1.12	62	31	4.1	2.0
E20C1	WE2M1		71	6	.97	51	48	30	28	1.01	62	38	14.8	9.0	.87	36	63	3.2	5.6
E40C1	WE4M1		89	12	.89	45	54	25	30	.71	33	47	1.2	1.6	.95	55	44	11.1	8.9
F40C1	WF4M1	83	74	12	1.76	64	36	22	12	1.77	60	38	5.8	3.6	1.78	67	32	9.6	4.6
H40C2	WH4M2	80	82	12	1.30	57	42	30	22	1.09	54	45	4.8	4.0	1.39	54	43	5.4	4.3
St. Johns '87																			
B40C2	WB4M2	83	54	12	1.29	47	52	119	132	1.72	54	46	69.1	59.9	1.00	45	54	23.6	28.2
C40C1	WC4M1	87	35	12	1.26	46	54	61	72	1.07	61	36	18.0	10.7	1.39	55	27	3.1	1.5
C40C3	WC4M3	71	77	12	1.30	43	54	42	53	1.15	70	23	13.9	4.7	1.21	52	42	12.1	9.7
D80C1	WD8L1	84	80	24	1.02	54	44	24	19	.99	51	49	8.8	8.6	.99	42	46	5.3	5.8
St. Johns '88																			
A50C1	WA5M1	97	71	15	.90	68	32	188	89	.94	31	69	9.6	21.0	.89	47	35	8.6	6.4
A80C1	WA8M1	77	54	24	1.10	39	61	59	93	1.05	34	61	5.3	9.4	1.08	26	72	5.0	14.1
B50C1	WB5L1	99	68	15	.98	42	56	94	125	.89	34	66	24.2	46.5	.92	48	49	13.7	14.1
C40C3	WC4M3	82	71	12	1.45	79	7	27	3	1.46	42	27	.8	.5	1.47	22	41	.4	.7
C80C1	WC8M1	57	65	24	1.23	62	31	20	10	1.24	38	43	1.4	1.6	1.24	34	44	1.2	1.6
D80C1	WD8L1	93	80	24	1.09	55	29	22	12	1.09	51	31	2.1	1.3	1.09	51	31	2.1	1.3

Statistical Analyses:

Tables 11 and 12 provide the results of the linear regression analyses performed. The analyses codes (I.A. through V.B.) refer to the linear regression descriptions provided in the Statistical Analyses part of the Methodology section. The data used for the regression analyses are provided by Appendix C (scatter plots) and Appendix D (statistical summaries).

The field data produced the following water table depth and fluctuation linear regression equations (with the greatest r^2's and least p statistic values) by site and by crop:

a. Ban '86: cyield = 64.5 + 0.283 atimea
(r^2=0.442, p=0.015)

b. Ban '87: cyield = 49.8 + 9.47 jwtd + 0.437 jtimea
(r^2=0.985, p=0.015)

c. SJ_2 '87: cyield = 195 - 126 jwtd + 1.51 jdfi
(r^2=0.997, p=0.005)

d. SJ_2 '88: cyield = 71.9 + 197 adista
(r^2=0.447, p=0.147)

e. Ban '86: syield = 26.9 + 64.2 jwtd - 1.11 jdfi
(r^2=0.825, p=0.002)

f. Ban '87: syield = 98.8 - 9.68 jwtd -2.07 jwfi
(r^2=0.768, p=0.054)

g. SJ_2 '87: syield = 138 - 66.5 awtd
(r^2=0.360, p=0.400)

h. SJ_2 '88: syield = 93.3 - 0.554 atimea
(r^2=0.883, p=0.005)

The field data produced the following water table depth and fluctuation linear regression equations (with the greatest r^2's and least p statistic values) by site and by independent variable:

_timea:

a. Ban '86: cyield = 64.1 + 0.283 atimea
(r^2=0.442, p=0.072)

b. Ban '87: cyield = 49.8 + 9.47 jwtd + 0.437 jtimea
(r^2=0.985, p=0.015)

c. SJ_2 '87: cyield = 63.9 + 0.452 jtimea
(r^2=0.566, p=0.248)

d. SJ_2 '88 cyield = 149 - 43.7 awtd - 0.359 atimea
(r^2=0.445, p=0.413)

e. Ban '86: syield = 34.4 + 39.0 jwtd - 0.033 jtimea
(r^2=0.618, p=0.034)

f. Ban '87: syield = 133 + 19.8 awtd - 0.644 atimea
(r^2=0.711, p=0.084)

g. SJ_2 '87 syield = 189 - 2.50 stimea
(r^2=0.317, p=0.437)

h. SJ_2 '88: syield = 93.3 - 0.554 atimea
(r^2=0.883, p=0.005)

_timeb:

a. Ban '86: cyield = 92.9 - 0.296 atimeb
(r^2=0.367, p=0.111)

b. Ban '87: cyield = 86.7 + 9.94 jwtd - 0.349 jtimeb
(r^2=0.936, p=0.064)

c. SJ_2 '87: cyield = 12 - 0.706 jtimeb
(r^2=0.547, p=0.260)

d. SJ_2 '88: cyield = 54.0 + 0.794 atimeb
(r^2=0.384, p=0.189)

e. Ban '86: syield = 32.2 + 40.0 jwtd + 0.002 jtimeb
(r^2=0.616, p=0.035)

f. Ban '87: syield = 68.8 - 21.2 awtd + 0.707 atimeb

(r^2=0.634, p=0.134)

g. SJ '87: syield = 156 - 1.94 atimeb
(r^2=0.307, p=0.445)

h. SJ '88 syield = -17.5 + 43.4 awtd + 0.981 atimeb
(r^2=0.867, p=0.049)

_wfi:

a. Ban '86: cyield = 83.3 - 0.139 swfi
(r^2=0.203, p=0.224)

b. Ban '87: cyield = 76.3 + 1.19 awfi
(r^2=0.797, p=0.041)

c. SJ '87: cyield = 148 - 70.2 jwtd + 0.930 jwfi
(r^2=0.841, p=0.399)

d. SJ '88: cyield = 77.1 + 0.530 jwfi
(r^2=0.362, p=0.206)

e. Ban '86: syield = 35.0 + 45.6 jwtd - 0.812 jwfi
(r^2=0.729, p=0.010)

f. Ban '87: syield = 98.8 - 9.68 jwtd - 2.07 jwfi
(r^2=0.768, p=0.054)

g. SJ '87: syield = 79.2 - 0.256 swfi
(r^2=0.330, p=0.426)

h. SJ '88: syield = 104 - 24.5 awtd - 1.38 awfi
(r^2=0.632, p=0.223)

_dfi:

a. Ban '86: cyield = 85.7 - 0.216 sdfi
(r^2=0.238, p=0.183)

b. Ban '87: cyield = 78.1 + 0.639 adfi
(r^2=0.308, p=0.332)

c. SJ '87: cyield = 195 - 126 jwtd + 1.51 jdfi
(r^2=0.997, p=0.061)

d. SJ '88: cyield = 73.9 + 1.98 adfi
(r^2=0.415, p=0.167)

e. Ban '86: syield = 26.9 + 64.2 jwtd - 1.11 jdfi
(r^2=0.825, p=0.002)

f. Ban '87: syield = 93.1 - 8.11 jwtd - 0.872 jdfi
(r^2=0.619, p=0.145)

g. SJ_2 '87: syield = 78.6 - 0.278 sdfi
(r^2=0.293, p=0.459)

h. SJ_2 '88: syield = 81.1 - 9.2 awtd - 0.52 adfi
(r^2=0.032, p=0.952)

The field data produced the corn and soybean relative yield (cyield and syield) vs. lateral spacing and water management zone (spacing and zone) regression equations:

a. Ban '86: cyield = 78.9 - 0.003 spacing
(r^2=0.000, p=0.995)

b. Ban '87: cyield = 89.9 - 0.679 spacing
(r^2=0.907, p=0.012)

c. SJ_2 '87: cyield = 76.7 + 0.306 spacing
(r^2=0.068, p=0.740)

d. SJ_2 '88: cyield = 111 - 1.43 spacing
(r^2=0.254, p=0.308)

e. Ban '86: syield = 61.3 - 0.324 spacing
(r^2=0.059, p=0.500)

f. Ban '87: syield = 69.0 + 1.17 spacing
(r^2=0.494, p=0.078)

g. SJ_2 '87: syield = 30.7 + 2.06 spacing
(r^2=0.340, p=0.417)

h. SJ_2 '88: syield = 75.2 - 0.372 spacing
(r^2=0.059, p=0.643)

i. Ban '86: cyield = 76.6 + 0.695 zone
(r^2=0.048, p=0.569)

j. Ban '87: cyield = 86.7 - 0.812 zone
(r^2=0.206, p=0.442)

k. SJ_2 '87: cyield = 79.8 + 0.500 zone
(r^2=0.003, p=0.942)

l. SJ_2 '88: cyield = 89.7 - 2.36 zone
(r^2=0.033, p=0.732)

m. Ban '86: syield = 50.5 + 1.97 zone
(r^2=0.407, p=0.047)

n. Ban '87: syield = 84.1 - 0.62 zone
(r^2=0.018, p=0.772)

o. SJ_2 '87: syield = 22.5 + 13.0 zone
(r^2=0.252, p=0.498)

p. SJ_2 '88: syield = 57.1 + 4.73 zone
(r^2=0.447, p=0.147)

Discussion

Meteorological Data:

As can be seen from Figures 8 through 15, from 1986 through 1988 the growing seasons became progressively hotter and dryer. During 1986 the growing season rainfall was above normal for the area and area irrigation systems saw very little use. The 1987 growing season had much less rainfall beginning before planting until an extreme precipitation event in early September. Area producers with irrigation systems did irrigate in 1987. The 1988 growing season was extremely dry. As can be seen from Figure 9 practically no rainfall fell during May, June and July. Crops grown in the area without benefit of irrigation had greatly reduced yields in 1988.

Table 11. Coefficients of determination (r2) resulting from linear regression analyses of data from the Bannister and St. Johns sites (one dependent variable).

ANAL'S	CROP	BAN'86	BAN'87	SJ'87	SJ'88	REGRESSION VARIABLES
I.A.	corn	0.031	0.001	0.132	0.319	cyield,swtd
I.B.	corn	0.011	0.563	0.307	0.016	cyield,stimeb
I.C.	corn	0.000	0.653	0.095	0.017	cyield,stimea
I.D.	corn	0.238	0.094	0.050	0.332	cyield,sdfi
I.E.	corn	0.203	0.352	0.024	0.263	cyield,swfi
II.A.	corn	0.015	0.000	0.000	0.324	cyield,jwtd
II.B.	corn	0.094	0.399	0.547	0.001	cyield,jtimeb
II.C.	corn	0.142	0.455	0.566	0.107	cyield,jtimea
II.D.	corn	0.015	0.146	0.032	0.357	cyield,jdfi
II.E.	corn	0.031	0.042	0.066	0.362	cyield,jwfi
III.A.	corn	0.014	0.012	0.000	0.337	cyield,awtd
III.B.	corn	0.367	0.278	0.031	0.384	cyield,atimeb
III.C.	corn	0.442	0.476	0.051	0.092	cyield,atimea
III.D.	corn	0.041	0.308	0.067	0.415	cyield,adfi
III.E.	corn	0.079	0.797	0.011	0.098	cyield,awfi
I.A.	soyb'n	0.329	0.170	0.231	0.000	syield,swtd
I.B.	soyb'n	0.220	0.000	0.101	0.224	syield,stimeb
I.C.	soyb'n	0.203	0.005	0.317	0.374	syield,stimea
I.D.	soyb'n	0.105	0.001	0.293	0.000	syield,sdfi
I.E.	soyb'n	0.009	0.001	0.330	0.181	syield,swfi
II.A.	soyb'n	0.616	0.329	0.059	0.007	syield,jwtd
II.B.	soyb'n	0.211	0.203	0.000	0.422	syield,jtimeb
II.C.	soyb'n	0.124	0.043	0.002	0.226	syield,jtimea
II.D.	soyb'n	0.060	0.482	0.121	0.006	syield,jdfi
II.E.	soyb'n	0.006	0.556	0.092	0.008	syield,jwfi
III.A.	soyb'n	0.002	0.055	0.360	0.000	syield,awtd
III.B.	soyb'n	0.028	0.188	0.307	0.353	syield,atimeb
III.C.	soyb'n	0.018	0.273	0.282	0.883	syield,atimea
III.D.	soyb'n	0.003	0.016	0.002	0.015	syield,adfi
III.E.	soyb'n	0.025	0.012	0.000	0.401	syield,awfi
V.A.	corn	0.000	0.907	0.068	0.254	cyield,spacing
V.B.	corn	0.048	0.206	0.003	0.033	cyield,zone
V.A.	soyb'n	0.059	0.494	0.340	0.059	syield,spacing
V.B.	soyb'n	0.407	0.018	0.252	0.447	syield,zone

Agronomic Data:

Each water table management zone and pipe lateral spacing treatment at each site was seeded to corn and soybeans. The agronomic decisions were made by the agricultural producers who owned the sites. Those producers also performed all agronomic operations. Except for soybean seeding rate and method, the agronomic practices used at each site were typical for agricultural production in south-central Michigan.

The soybean seed was drilled at approximately 150 mm spacing at each site. This is customary for irrigated soybeans in many north central states but not typical for Michigan. Due to the producers not being familiar with soybean seed drilling operations, considerable variation in population rates were observed at each site.

Relative yield with yield goal as the denominator was used to compare treatments and for subsequent statistical analysis. Relative yield was chosen so that yield vs. water table variable relationships derived from the field data (from two sites and three growing seasons) are independent of site and climatic variables. The data suggests that none of the treatments can be considered as controls in which maximum yield possible is obtained. Therefore, it is felt yield goal is a more appropriate datum for calculating relative yield. Using relative yield with yield goal in the denominator also allows the relationships between yield and water table parameters to be used in a mathematical model

Table 12. Coefficients of determination (r2) resulting from linear regression analyses of data from the Bannister and St. Johns sites (two dependent variables).

ANAL'S	CROP	BAN'86	BAN'87	SJ'87	SJ'88	REGRESSION VARIABLES
IV.A.	corn	0.039	0.806	0.560	0.359	cyield,swtd,stimeb
IV.B.	corn	0.031	0.826	0.157	0.409	cyield,swtd,stimea
IV.C.	corn	0.238	0.117	0.442	0.373	cyield,swtd,sdfi
IV.D.	corn	0.203	0.599	0.461	0.337	cyield,swtd,swfi
IV.E.	corn	0.096	0.936	0.567	0.391	cyield,jwtd,jtimeb
IV.F.	corn	0.142	0.985	0.596	0.393	cyield,jwtd,jtimea
IV.G.	corn	0.017	0.497	0.997	0.393	cyield,jwtd,jdfi
IV.H.	corn	0.064	0.048	0.841	0.394	cyield,jwtd,jwfi
IV.I.	corn	0.367	0.325	0.555	0.414	cyield,awtd,atimeb
IV.J.	corn	0.443	0.512	0.339	0.445	cyield,awtd,atimea
IV.K.	corn	0.087	0.367	0.088	0.423	cyield,awtd,adfi
IV.L.	corn	0.112	0.825	0.014	0.341	cyield,awtd,awfi
IV.A.	soyb'n	0.451	0.292	0.410	0.317	syield,swtd,stimeb
IV.B.	soyb'n	0.457	0.318	0.375	0.646	syield,swtd,stimea
IV.C.	soyb'n	0.331	0.186	0.329	0.001	syield,swtd,sdfi
IV.D.	soyb'n	0.381	0.419	0.341	0.431	syield,swtd,swfi
IV.E.	soyb'n	0.616	0.337	0.061	0.477	syield,jwtd,jtimeb
IV.F.	soyb'n	0.618	0.346	0.059	0.540	syield,jwtd,jtimea
IV.G.	soyb'n	0.825	0.619	0.478	0.007	syield,jwtd,jdfi
IV.H.	soyb'n	0.729	0.768	0.125	0.009	syield,jwtd,jwfi
IV.I.	soyb'n	0.039	0.634	0.370	0.867	syield,awtd,atimeb
IV.J.	soyb'n	0.030	0.711	0.366	0.884	syield,awtd,atimea
IV.K.	soyb'n	0.007	0.083	0.465	0.032	syield,awtd,adfi
IV.L.	soyb'n	0.025	0.104	0.563	0.632	syield,awtd,awfi

that can be applied independently of site location and growing season year.

System Operation Data:

For the growing seasons studied, the water table controls at both sites were set to the desired water table elevation immediately following spring field operations. The initiation of irrigation water pumping to the site was started at the point in time where rainfall was not maintaining or raising the water table. After start of pumping, pumping was continuous until the crop matured near the end of August.

The rate of irrigation water supply at the Bannister site was set at all times to cause water discharge at the water management zone outlet. Thus the supply of irrigation water to the Bannister site water table management zones was not limited to the maintenance of the water table depth within the zone. To better study the effect of water table fluctuation on plant biomass production, irrigation pumping was not stopped during or following rainfall events. At the Bannister site, the water table controls were varied during the growing season to cause water table fluctuation (see Table 6).

At the St. Johns site the soil profile allows high lateral seepage to occur. This resulted in the need to begin pumping at an early date (6/12/87 and 5/24/88). The high rate of lateral seepage also prohibited holding the water table in one water management zone at a different level than in adjacent zones. The level of the water table was controlled by the lateral seepage and crop use of the water in relation to the pumping rate to the field. An irrigation water pumping capacity of 0.9 L/(s·ha) was not sufficient to maintain the water table at design depths during the growing season. Thus during most of the growing season the elevation of the water table control weir had no effect on water table depth for any zone except zone D, the drainage only zone.

Ground Water Data:

At both sites many more observation wells were installed than were used. It was found the observation wells located nearest the center of the water management zone and midway between pipe laterals provided data that best represented the mean water table elevation within the zone. Those wells are identified by the letter 'M' in the fourth place of the well identification code.

At both sites instrumentation breakdowns and water tables above and below the capability of the instrumentation to measure resulted in occasional lapses of water table data. The wells chosen for subsequent analyses are those whose data omissions are relatively infrequent and thus do not influence the analyses results. To relate observation well system output to water table elevation, the digital output for each well was compared to manual measurements of the depth to the water table made during each growing season. Because the output resulted from pressure transducers which provide a linear measurement of the water column at the observation well, the relationship between water table depth or elevation at an observation well vs. digital output is linear. Thus, relating digital output to field measured water table elevation for an observation well results in a calibration equation (the Table 8 regression equation) and a measurement of the functioning of the well (the Table 8 r^2).

Table 8 presents the results of the regression analyses for the observation wells for the study period at both sites. The wells shown all have a correlation coefficient squared greater than 0.800. Observation wells not shown in Table 8 were not operable or had a correlation coefficient squared less than 0.800.

The Table 8 regression equation slope differences are the result of each pressure transducer having a unique slope. The constant value of the regression equations represent the pressure transducer intercept and the elevation of the bubbler exit port within each well.

Table 8 shows the regression equation for the same observation well differed from year to year. These differences resulted from changes to the system being made during the winter months. For example between the 1986 and 1987 growing seasons, 700 mm H_2O capacity rated pressure transducers were replaced with transducers with a 1400 mm H_2O capacity rating. Other changes that caused year to year changes in the regression equation include changing the bubbler tube exit port elevation and changing the nitrogen tank pressure and bubbling rate.

Statistical Analyses:

The statistical analyses of the field data were made to evaluate the relationship between water table and relative yield for corn and soybeans for each of two soil types. The relationships explored include both depth and fluctuation of the water table.

Tables 9 and 10 provide the yield, water table depth and water table fluctuation data resulting from the field study. Table 11 provides the results of mean square linear regressions of yield vs. water table depth, water table variation and other variables.

One Dependent Variable Regressions:

From Table 11 it can be seen the following regression variables produced a coefficient of determination greater than 0.500 and a p statistic less than 0.200 for relative yield vs. either a mean water table depth or a water table fluctuation variable:

a. soybean yield vs. mean water table depth during July (Ban '86, r^2=0.616, p=0.007, syield=32.3+40.09jwtd)

b. corn yield vs. % time above mean water table depth for the season (Ban '87, r^2=0.653, p=0.098, cyield=69.1+0.303stimea)

c. soybean yield vs. % time above mean water table depth during August (SJ'88, r^2=0.883, p=0.005, syield=93.3-0.554atimea)

d. corn yield vs. % time below mean water table depth for the season (Ban '87, r^2=0.563, p=0.144, cyield=98.1-0.287stimeb

e. corn yield vs. wet stress fluctuation index for August (Ban '87, r^2=0.797, p=0.041, cyield=76.3+1.19awfi)

f. soybean yield vs. wet stress fluctuation index for July (Ban '87, r^2=0.556, p=0.054, syield=89.9-2.30jwfi)

The regression analyses of yield vs. mean water table provided only one data set with an r^2 greater than 0.500. It is not surprising that the data shows few high single variable linear regression coefficients of determination. The literature suggests for corn and soybeans there is an optimum water table depth for yield (Goins et al., 1966 and Williamson and van Schilfgaarde, 1965). Thus the relationship between yield and mean water table depth should not be linear.

It has been shown (Williamson and Kriz, 1970; Howell and Hiler, 1974; Zolezzi et al., 1978; Fausey et al., 1985; VanToai et al., 1987) that saturation of corn and soybean roots for varying lengths of time reduces yields. The literature further suggests that the yield reduction is related to the duration and extent of root system saturation (Kanwar et al., 1988). Likewise, root zone water deficient conditions lead to reduced yields with the reduction being related to the duration and degree of the deficiency. Thus it is expected that water table fluctuation does impact yield and that the relationship will be more linear than the yield vs. mean water table depth relationship. The regression analyses of the field data do indicate the water table fluctuation parameters (% time above and below mean water table depth and wet/dry stress fluctuation index) are more linear than the yield vs. mean water table depth relationship. This is evidenced by the fact that of the six single dependent variable regression equations with r^2 greater than 0.500 and p statistic less than 0.200, five have water table fluctuation dependent variables (b through f).

Examination of the five water fluctuation parameter regression equations shows consistency. An increase in water table fluctuation above the mean water table (b and e) and a decrease in water table fluctuation below mean water table (d) would have resulted in increased corn yield. Thus the signs of the single independent variable corn yield regression equations with r^2 greater than 0.500 are consistent and indicate corn yields at Bannister in 1987 would have been greater if the water table had risen into the root zone more often and/or for longer duration.

The soybean yield regression equations (a, c and f), while consistent, suggest the opposite. The negative coefficient of the % time above mean water table elevation regression equation (c) and the wet stress fluctuation index (f) both indicate the soybean yield at the St. John's site during 1988 was reduced due to the frequency and/or duration of the water table rising into the root zone during July and August. The regression coefficient for the mean depth to the water table during July, 1988 at the St. Johns site indicates a deeper water table (from less water table rise fluctuation) would have resulted in increased production.

The regression equations that best describe the effect of mean water table or water table fluctuation from the mean water table elevation on corn and soybean yield are:

a. cyield = 76.3 + 1.19 awfi for the Bannister site during the 1987 growing season (r^2=0.797, p=0.041)

b. syield = 32.3 + 40.9 jwtd for the Bannister site during the 1986 growing season (r^2=0.616, p=0.007)

c. syield = 93.3 - 0.554 atimea for the St. Johns site during the 1988 growing season (r^2=0.883, p=0.005)

However, the single dependent variable regression analyses do not provide conclusive evidence that corn or soybean yield is a function of either mean water table depth or water table fluctuation above and below the mean depth. This is not surprising because both mean water table depth and water table fluctuation parameters were treatment variables and thus neither were held constant. The single variable regression analyses results do indicate that the water table fluctuation parameters have a greater effect on corn and soybean yield than mean water table depth for the study location and time period. Further, the analyses results suggest that during 1987 at the Bannister site, the corn yield was reduced because of deficient soil water and at the St. Johns site in 1988, the soybean yield was reduced because the water table rose above the mean water table depth.

Two Dependent Variable Regressions:

Table 12 provides the results of least square linear regression analyses for data sets that include both mean water table depth and a water table fluctuation variable. The Table 12 results strongly indicate corn and soybean yield at the sites were influenced by both mean water table depth and water table fluctuation. This is reflected in the r^2 values obtained for the regression equations that included mean water table depth and one of the following water table fluctuation variables: % time below mean water table elevation, % time above mean water table elevation, water table fluctuation wet and dry stress indices and percent time above and below the mean water table elevation.

From Table 12, those regression variables that produced r^2's greater than 0.500 with p statistics less than 0.200 are:

a. corn yield vs. mean water table depth and percent of time below the mean water table elevation:
(Ban'87, r^2=0.806, p=0.194, cyield=96.7+6.92swtd-0.420stimeb)
(Ban'87, r^2=0.936, p=0.064, cyield=86.7+9.94jwtd-0.349jtimeb)

b. corn yield vs. mean water table depth and dry stress fluctuation index:
(SJ '87, r^2=0.997, p=0.051, cyield=195-126jwtd+1.51jdfi)

c. corn yield vs. mean water table depth and percent of time above the mean water table elevation:
(Ban'87, r^2=0.826, p=0.174, cyield=58.4+5.46swtd+0.390stimea)
(Ban'87, r^2=0.985, p=0.015, cyield=49.8+9.47jwtd+0.437jtimea)

d. soybean yield vs. mean water table depth and percent of time below the mean water table elevation:
(Ban'86, r^2=0.616, p=0.035, syield= 32.2+40.0jwtd+0.002jtimeb)
(Ban'87, r^2=0.634, p=0.134, syield= 68.8-21.2awtd+0.707atimeb)
(SJ '88, r^2=0.867, p=0.049, syield=-17.5+43.4awtd+0.981atimeb)

e. soybean yield vs. mean water table depth and dry stress fluctuation index:
(Ban'86, r^2=0.825, p=0.002, syield=26.9+64.2jwtd-1.11jdfi)
(Ban'87, r^2=0.619, p=0.145, syield=93.1-8.11jwtd-0.872jdfi)

f. soybean yield vs. mean water table depth and percent of time above the mean water table elevation:
(Ban'86, r^2=0.618, p=0.034, syield=34.4+39.0jwtd-0.033jtimea)
(Ban'87, r^2=0.711, p=0.084, syield=133 +19.8awtd-0.644atimea)
(SJ '88, r^2=0.884, p=0.040, syield=94.1-0.72awtd-0.554atimea)

g. soybean yield vs. mean water table depth and wet stress fluctuation index:
(Ban'86, r^2=0.729, p=0.010, syield=35.0+45.6jwtd-0.812jwfi)
(Ban'87, r^2=0.768, p=0.054, syield=98.8-9.68jwtd-2.07jwfi)

Corn Yield - Two Dependent Variables:

It can be concluded that during the 1987 growing season the corn yield at the Bannister site was strongly influenced by the combination: mean depth to the water table and fluctuation of the water table. The regression equations consistently show the 1987 Bannister corn yield was proportional to the mean depth to the water table and percent of time the water table is above the mean water table elevation (a and c). This suggests maximum yield would result from establishing a water table fairly deep within the soil profile, frequently raising the water table to the surface and immediately returning it to the original water table depth.

For the St. Johns site during 1987, the regression results are less conclusive but do indicate corn yield was inversely proportional to the mean water table depth and proportional to the dry stress water table fluctuation index. Thus, to increase yields, the water table would be established at a depth less than the mean water table depth that occurred in 1987 and the water table maintained at or above the mean water table depth.

For both Bannister and St. Johns, the regression analyses indicate that corn yield will increase if the water table is not allowed to fall below the water table depth established early in the season.

The regression analyses did not produce r^2's greater than 0.500 for corn yield during the 1986 season at the Bannister site nor the 1988 season at the St. Johns site. The yield differences observed at each site and for each season are influenced by both the experimental variables and other factors outside the control of the experiment such as spatial variability of soil properties, rainfall, tillage, planting, harvesting, plant health and hardiness, pesticide control, and fertilizer effectiveness as well as inaccuracies in measurement of the experiment variables. The lack of correlation of the Bannister site 1986 data is attributed to excessive disturbance of the clay soil during the installation of the subirrigation system in July, 1985 which persisted into 1986. This disturbance caused spatial variation of the soil structure and soil properties thus affecting soil water movement, root penetration, fertilizer utilization, etc. The excessive disturbance of the soil during system installation resulted in affecting yield to a greater extent than the experimental variables, mean water table depth and water table fluctuation.

For the St. Johns site 1988 growing season, the lowest corn yield of 77% from treatment A80C1 (see Table 10) appears to be an outlier point (and in fact that treatment had a greater infestation of weeds than the other treatments). However, performing the regression analyses without treatment A80C1 data did not result in linear regression equations with r^2 greater than 0.500 and p less than 0.200.

The regression equations that best describe the effect of mean water table depth and water table fluctuation from the mean water table elevation on corn yield are:

cyield = 49.8 + 9.47 jwtd + 0.437 jtimea for 1987 Bannister data and jwtd from 0.73 m to 1.77 m and jtimea from 38 to 68 (r^2=0.985, p=0.015)

cyield = 195 - 126 jwtd + 1.51 jdfi for 1987 St. Johns data and jwtd from .99 m to 1.72 m and jdfi from 8.8 to 69.1 (r^2=0.997, p=0.051)

Neither the 1986 Bannister site nor the 1988 St. Johns site provided data that related corn yield to mean water table depth and water table fluctuation from the mean water table elevation.

The two preceding regression equations for relative corn yield do accurately reflect the site conditions. The high clay content soil profile at the Bannister site allowed the water table to be maintained at a constant, but relatively shallow, depth throughout the growing season. Thus it is not surprising yield is improved by decreasing the percent time the water table fluctuates above the mean water table. The St. Johns site is characterized by difficulty in maintaining the water table at a shallow depth due to high lateral conductivity of the soil profile. The water table elevation achieved early in the season constantly dropped during the growing season. This appears to have resulted in the regression equation for the 1987 growing seasons showing crop yield improvement from decreasing the mean depth to the water table and increasing water table fluctuation. Thus for both sites, the 1987 data shows an increase in water table fluctuation would have resulted in increased corn yield.

Obviously, the preceding analyses of the corn yield regression equations suggest that factors other than mean depth and fluctuation of the water table are important to corn grain production. It is assumed for the 1986 and 1988 growing seasons the lack of corn yield correlation is the result of other factors masking the water table depth and fluctuation factors. The analyses do show that site soil factors influence the maintenance of a water table and weather factors, including rainfall volumes and timing, strongly influence the relationship of both mean water table depth and water table fluctuation to corn yield. Further, the data supports the hypothesis that for a site in which a relative constant water table elevation can be maintained at a shallow depth, the subirrigation system should be operated to minimize fluctuation of the water table above the desired constant water table depth. For a site that will not allow the maintenance of a constant water table throughout the growing season, the subirrigation system should be operated to cause the water table to frequently raise for short time durations. In actual practice this means for a constant water table site the system operator would operate the system in a drainage mode following rainfall events that cause a rise in the water table. For a falling water table site the system operator would operate the system in a drainage mode following rainfall events only if the combination of event frequency, duration or volume cause the water table to rise for an extended period of time. The end result is that for a constant water table site, the operator has more control over the yield but much more work is required. For a falling water table site, the operator is more dependent upon rainfall but less work is involved.

The data suggests that at a site that has constant water table elevation depth capability, the best operation scenario is to allow the water table, over the season, to recede at a rate less than the rate of corn root elongation. This would allow an irrigation rate less than the rate of evapotranspiration plus deep and lateral seepage and reduce the work involved in operating the system. There is a need to study this concept further.

Certainly, the differences in the relative corn yield regression equations (Tables 11 and 12) illustrate the need to consider site, weather and crop factors in a design procedure for water table management systems.

Soybean Yield - Two Dependent Variables:

The Table 12 regression equations for soybean yield show that for both the 1986 and 1987 growing seasons at the Bannister site the yield was related to the combination of mean water table depth and water table fluctuation parameters.

The relative soybean yield regression equations show, generally for the 1986 season at Bannister, the yield was inversely proportional to the percent time above the mean water table elevation in July, the July wet stress water table fluctuation index and the July dry stress water table fluctuation index each along with a direct proportional relationship with the July mean depth to the water table.

The 1987 Bannister regression analyses show the water table fluctuation parameters (July percent time above the mean water table and July wet and dry stress water table fluctuation indices) all being inversely proportional to soybean relative yield as was the case for the 1986 Bannister data. However, opposite to the 1986 results, the 1987 Bannister regression analyses show the mean depth to the water table (during July) being inversely proportional to yield.

For the 1988 season at St. Johns, the two equations with r^2 greater than 0.500 and p less than 0.200 indicate increased soybean yield would have resulted if the mean depth to the water table was less in July with less fluctuation of the water table above the July mean water table elevation.

The St. Johns site 1987 growing season did not produce any water table depth/fluctuation regression equations with an r^2 greater than 0.500 and a p less than 0.200. Examination of the soybean yield data for that site and year (see Table 10) shows that the treatment C40C1 relative yield of 35 percent may be an outlier (the yield is much lower with the water table parameters being similar to the other treatments). The weed infestation in treatment C40C1 was observed to be much greater than for the remainder of the field. However, because the deletion of treatment C40C1 data reduces the sets of data to three, regression equations with more than a single dependent variable are not meaningful.

Thus the analyses suggest for 1987 at the Bannister site and 1987 at the St. Johns site, the soybean yield would have benefited from a higher mean water table elevation and less fluctuation of the water table above and below the mean water table elevation. During 1986 at Bannister a lower mean water table elevation and less water table fluctuation would have improved soybean yield.

The soybean yield regression equations with both mean depth to the water table and water table fluctuation above the mean water table elevation with the best r^2's are:

> syield = 35.0 + 45.6 jwtd - 0.812 jwfi for 1986 Bannister data with jwtd from 0.45 m to .72 m and jwfi from 4.3 to 14.5 (r^2=0.729 p=0.010)
>
> syield = 98.8 - 9.68 jwtd - 2.07jwfi for 1987 Bannister data with jwtd from 0.71 m to 1.77 m and jwfi from 1.6 to 9.0 (r^2=0.768, p=0.054)
>
> syield = 94.1 - 0.72 awtd - 0.554 atimea for 1988 St. Johns data with awtd from 0.89 m to 1.47 m and atimea from 31% to 72% (r^2=0.884, p=0.040)

Regression Without Outliers:

A close examination of the Table 10 data reveals that for the 1987 St. Johns data set, the treatment C40C1 relative soybean yield may be an outlier as is the 1988 St. Johns data set treatment A80C1 relative corn yield.

Performing the regression analyses without St. Johns 1987 treatment C40C1 and St. Johns 1988 treatment A80C1 data produces the following soybean yield regression equations with r^2 greater than 0.400 and p less than 0.250:

a. syield = 118 - 36.9 jwtd, r^2=0.989, p=0.066, SJ '87
b. syield = 87.7 - 0.281 sdfi, r^2=0.995, p=0.047, SJ '87
c. syield = 86.7 - 0.241 swfi, r^2=0.964, p=0.122, SJ '87
d. syield = 83.3 - 0.425 jdfi, r^2=0.999, p=0.019, SJ '87
e. syield = 81.4 - 0.455 jwfi, r^2=0.972, p=0.108, SJ '87
f. syield = 90.6 - 1.48 adfi, r^2=0.928, p=0.172, SJ '87
g. syield = 87.6 - 1.19 awfi, r^2=0.997, p=0.037, SJ '87
h. syield = 50.2 + .531 jtimeb, r^2=0.544, p=0.155, SJ '88
i. syield = 96.9 - .647 atimea, r^2=0.678, p=0.087, SJ '88

The results show the same trends as resulted from the regression analyses using all of the data. The regression analyses for the St. Johns 1987 data without treatment C40C1 provides regression equations with r^2's greater than 0.500 for soybean yield that were not obtained previously.

Conclusions

1. The diurnal fluctuation of the water tables measured at each site and for each growing season indicates

evaporated and transpired soil water was in part being replenished from the water table.

2. Comparing the r^2 and p statistics of the spacing and zone regression equations with the regression equations arranged by site and by crop and regression equation arranged by site and dependent variable, it is concluded that water table depth fluctuation parameters are better predictors of corn and soybean yield than lateral spacing or water table management zone for the sites and growing seasons studied.

3. The regression analyses of the field data from the Bannister and St. Johns field sites did not provide an equation for design that relates corn or soybean yield to mean water table depth or water table fluctuation above or below mean water table elevation consistent for both sites and/or all three years. However, the analyses did provide insight into the relative importance of those water table parameters in situations where the agricultural producer has the opportunity to provide a measure of water table control.

4. Examination of the field data scatter plots (Appendix D) coupled with the results of the single independent

variable regression analyses indicate water table fluctuation parameters have a greater effect on corn and soybean yield than does mean depth to the water table.

5. Two out of three years soybean yields at the field sites were more affected by the fluctuating water table parameters than were corn yields at the field sites.

6. For the research sites and study period, generally the water table fluctuation parameter regression coefficients were positive for fluctuation above the mean water table for corn yield and negative for soybean yield. Those coefficients were negative for fluctuation below the mean water table for corn yield and positive for soybean yield.

7. The water table fluctuation wet/dry stress index appears to be a valid procedure for quantifying the combined effect of time and accumulated distance the water table is above/below the mean water table elevation. However, the data did not show that the water stress fluctuation wet/dry stress index offers more prediction accuracy than the percent of time above/below the mean water table elevation parameter.

8. There is a need to continue studies of water table depth and fluctuation effects on corn and soybean production and other crops under a variety of soil and climatic conditions. For continued work, greater control of the water table within a treatment and other crop production variables other than water table depth and fluctuation is needed. Also, the treatments should be located randomly with three or more replications.

9. The data suggests that at a site that has constant water table elevation depth capability, the best operation scenario is to allow the water table, over the season, to recede at a rate less than the rate of corn root elongation. This would allow an irrigation rate less than the rate of evapotranspiration plus deep and lateral seepage and reduce the work involved in operating the system. There is a need to study this concept further.

10. The effect of water table depth and fluctuation on corn and soybean yield needs to be considered in the design process for water table management systems. The field data regression analyses results suggest the critical design parameter is to return the water table to the design depth following frequent water table raises for corn production and following rainfall events for

soybean production. To account for both the frequency and extent of water table rise, the system design criteria should utilize the water table fluctuation wet stress index.

11. The study did not produce design criteria in which relative corn and soybean yield is dependent upon only water table depth and/or fluctuation parameters. Thus the objective of quantifying water table management operation parameters that influence plant biomass production was not realized. A single mathematical model relating relative yield to water table depth and water table fluctuation independent of field location, soil profile and growing season could not be derived from the field data.

The study does suggest that for corn production at the Bannister and St. Johns sites and with a mean water table depth of 0.5 m the regression equation:

$$Y = B0 + B1 * X \qquad [3]$$

can be used for water table management system design with:

Y = relative corn yield in %
X = jwfi in m*h/h
B0 = 77
$0.5 <= B1 <= 1.2$

Likewise, the data suggests that for soybean production at the Bannister and St. Johns sites (also with the mean water table depth at 0.5 m) the regression equation:

$$Y = B0 - B1 * X \qquad [3a]$$

would have:

Y = relative soybean yield in %
X = awfi in m*h/h
B0 = 92
1.4 <= B1 <= 2.1

Letting B1 be midway between the range given, for corn production the design equation with the water table fluctuation wet stress index as a variable is:

$$cyield = 77 + 0.85\ awfi \qquad [4]$$

and for soybean production is:

$$syield = 92 - 1.75\ jwfi \qquad [4a]$$

both with the mean water table depth at 0.5 m.

WATER TABLE MANAGEMENT SYSTEM DESIGN

Methodology

System Components:

A water table management system consists of perforated underground pipe spaced at regular intervals. These pipe are called laterals and are arranged in zones determined by the elevation variance of the soil surface within the zone. The laterals within each zone discharge to an underground collector pipe called a submain. The submain for each zone outlets to an underground pipe called a main. The number and size of the zones, submains and mains is a function of the topography of the site.

Water table management systems provide the capability to lower the water table (subsurface drainage mode) or raise and maintain the water table at a given elevation (subirrigation modes). Each zone requires a water table control structure located in the submain immediately downstream of the zone. The water table control structure has the capability to be set to allow free drainage (subsurface drainage mode) or to establish a water table upstream of the structure at a desired elevation (controlled drainage and subirrigation modes). Irrigation intake structures, vertical pipes from the submain to the ground surface, are provided for irrigation water access to the underground system during times when rainfall does not maintain the water table at the desired elevation. The irrigation water is pumped from the source to the field through irrigation water supply pipes.

A water table management system thus consists of laterals, submains, mains, water table control structures, irrigation intake structures, irrigation water supply pipes, a pump and a power supply.

System Operation:

A water table management system has three modes of operation. The subsurface drainage operation mode is used to lower a water table that is above the elevation of the laterals by draining water from the soil profile via the underground pipe system. The controlled drainage operation mode is used to capture rainfall to raise or maintain a water table above the elevation of the laterals. The subirrigation mode is used to raise or maintain a water table above the elevation of the laterals by providing irrigation water to the soil profile via the underground pipe system.

The field research suggests system operation must consider both the depth to the water table during the growing season and the fluctuation of the water table. Further, the research suggests that water table fluctuation has a greater effect on yield than does mean water table depth.

SIDESIGN Computer Model:

An objective of this research was to develop a model for the efficient design of water table management systems that will allow the system to be operated for maximum plant biomass production economic efficiency. That objective was met by developing the computer module SIDESIGN.

The present version of the SIDESIGN computer model has the following requirements and attributes:

1. The model is operational on the following minimum system configuration:
   a. IBM personal computer or compatible with a minimum of 256 k RAM memory and a single floppy disk.
   b. CGA or higher resolution monitor, monochrome or color.
   c. 80 character line printer.

2. Model operation is interactive with the user responding

to prompts displayed on the monitor.

3. The model does not require additional software other than the operating system software (MSDOS or PCDOS Version 2.11 or higher).

4. The model is written in the QuickBASIC compiler language (Version 4.5) from Microsoft Corporation, Redmond, Washington, USA.

MODEL FORMAT

The model is in modular format. The present version of the model has the following modules:

* SIRAIN
* SILSPACE
* SIMAIN
* SIECON

A detailed description of each module follows.

SIRAIN DESCRIPTION

The SIRAIN module is used to calculate the design rainfall event to be used for subsequent calculations. The module uses historic growing season rainfall records provided by the model user. The input data may be provided as a text file or by interactive keyboard input.

Data Input:

The model user inputs the number of years (NumberOfYears) to be analyzed, the growing season start date (SeasonStartDate) and end date (SeasonEndDate) and the daily rainfall for each day of the growing season (including 0.0 rainfall days) for each year {rain(y,d)}. The data input can be interactive with the user responding to screen prompts or by the user inputting the name of the data disk file.

For diskfile input, the data must follow the following format:

Line 1

NumberOfYears, SeasonStartDate, SeasonEndDate

Line 2

year(n)

Line 3

rain(y,d)

Line 3 is followed by rainfall for each day of year 'n' starting with the SeasonStartDate and ending with the SeasonEndDate. Lines 2 and 3 are repeated for each year of historic data.

Calculations:

The module uses the input data to calculate and output the 50% probability (2 year recurrence interval) and 10% probability (10 year recurrence interval) daily rainfalls by month and growing season. The module also calculates and outputs the number of rainfall events per month and growing season at the 50% probability level.

To calculate the 50% and 10% probability daily rainfalls, the historic daily rainfall data is ranked in decreasing order, excluding 0 rainfall days, and the recurrence interval calculated by the mathematical model (Schwab, et al., 1981):

$$T = \frac{N+1}{n} \qquad [5]$$

where: T = recurrence interval, yr

N = total number of daily rainfall events, unitless

n = rank of rainfall events arranged in descending order, unitless

All of the rainfall events are ranked by month and by growing season. For the 2 year recurrence interval rainfall, equation 5 requires the rainfall that falls midpoint in each ranking be determined and provided as output. If at any time the number of ranked rainfall events is not odd, the smallest rainfall value is dropped from the ranking. This insures that the 2 year recurrence can always be calculated. The same rankings are used to determine the 10 year recurrence interval rainfall. That ranking of that rainfall is at 10% of the total number of rainfall events for each ranking.

Example:

A numeric example of the procedure for determining the 2 year recurrence rainfall follows:

Assume the historical daily rainfall (in mm) is from 1980 through 1982 and the growing season is June 1 through August 31. The daily rainfall amounts for the days rainfall occurred for those years and months is:

	June	July	August
1980	18	3	9
	2	12	3
	11	4	5
			21
1981	5	7	11
	9	1	3
	12		4
	3		

1982	2	4	21
	1	7	1
	14	11	5
		6	

To obtain the 50% probability rainfall (2 year recurrence interval) by month and growing season the above data is ranked as follows:

June: 18, 14, 12, 11, 9, 5, 3, 2, 2, 1

July: 12, 11, 7, 7, 6, 4, 4, 3, 1

August: 21, 21, 11, 9, 5, 5, 4, 3, 3, 1

Season: 21, 21, 18, 14, 12, 12, 11, 11, 11, 9,
9, 7, 7, 7, 6, 5, 5, 5, 4, 4,
4, 3, 3, 3, 2, 2, 1, 1, 1

For the June and August data, the 1 mm rainfall is dropped from the ranking so as to have an odd number of rainfall events in each of the four rankings. This results in N values for equation 5 equal to 9, 9, 9 and 29 for June, July, August and the season, respectively. Applying equation 5 to the data produces 2 year recurrence values of daily rainfall equal to 9 mm, 6 mm, 5 mm and 6 mm for June, July, August and the season respectively.

The model uses a similar procedure to determine and output the number of rainfall occurrences for each month and the growing season. The example follows:

For June, 3 events occurred in 1980, 4 in 1981 and 3 in 1982. Likewise, for July 3, 2 and 4 events occurred for 1980, 1981 and 1982 respectively; for August 4, 3 and 3 occurred for 1989, 1981 and 1982 and for the season 10, 9 and 10 events occurred for those same three years. Ranking the number of events by year:

June: 4, 3, 3

July: 4, 3, 2

August: 4, 3, 3

Season: 10, 10, 9

Applying equation 5 to the data results in 50% probability for number of rainfall events at 3, 3, 3 and 10 events for June, July, August and the season, respectively.

The preceding example is to illustrate the procedure only. To determine recurrence interval rainfalls and number of events for design, the period of rainfall records should equal or exceed 20 years. The SIRAIN module has the capability to analyze up to 30 years of daily rainfall data for a 12 month growing season per year.

The procedure is a modification of a partial series duration analysis. For further information the reader is referred to Chow, 1964.

SILSPACE DESCRIPTION

The water table system components that limit control of depth to the water table and rate of fluctuation are the depth, spacing and hydraulic capacity of the laterals, the hydraulic capacity of the submains and mains, the operational capability of the water table control structures and the capacity of the water supply system.

The SILSPACE module allows the combined effects of those components on the operation of subirrigation systems to be investigated. The SILSPACE module allows the user to evaluate system design alternatives on system performance in terms of water table depth and water table fluctuation.

SILSPACE consists of five sections: data input, initial calculations, steady state analysis, transient analysis and results output.

Data Input:

User input data describes the soil profile, the design rainfall event, the system components and the system operation. The model uses those data to compute and output the lateral spacing and discharge capacity required for steady state supply of irrigation water and steady state subsurface drainage. Next, the vertical rise of the water table due to infiltration of the design rainfall is calculated. This is followed by transient analysis to determine the time and discharge rates for the water table to return to the levels preceding the rainfall event.

A description of the data that must be provided by the model user follows:

System Variables:

depth to the lateral pipe.............TileDepth
diameter of the lateral pipe..........TileDiameter
minimum grade of the lateral pipe.....TileGrade
length of the lateral pipe............TileLength

For Subirrigation:

depth to water table at lateral.......siWTdepthLateral
depth to water table at midpoint......siWTdepthMidpoint

For Subsurface Drainage:

depth to water table at lateral.......sdWTdepthLateral
depth to water table at midpoint......sdWTdepthMidpoint
design subirrigation rate.............sirate
design subsurface drainage rate.......drrate
design storm runoff...................runoff
design storm occurrences..............events
depth to weir following rainfall......WeirDepth

Soil Variables:

depth to barrier......................BarrierDepth
number of soil layers.................nlayers

For Each Soil Layer:

layer thickness.......................th
saturated hydraulic conductivity......hydc
water content at saturation...........sat
water content at drained upper limit..dul

The input data required, for the most part, is self explanatory and easily obtained. The water content at saturation (sat) is the volumetric soil water content when the soil is saturated. The drained upper limit (dul) is the volumetric water content that results from complete soil water drainage from the soil layer without evaporation or transpiration. The 'sat' and 'dul' terms are further described by Ritchie et al., 1986.

The model allows data input from a diskfile or interactively. A data input diskfile requires the data to be arranged in the following sequence:

Line 1

BarrierDepth, nlayers

Line 2 (Note: Line 2 data are provided for each soil layer in sequence beginning with the surface layer.)

th, hydc, sat, dul

Line 3

TileDepth, TileDiameter, TileGrade, TileLength, siWTdepthMidpoint, siWTdepthLateral, sdWTdepthMidpoint,

sdWTdepthLteral

Line 4

sirate, drrate, rainfall, rainfall occurrences, runoff curve number, WeirDepth

Initial Calculations:

SILSPACE first calculates the infiltration resulting from the user inputted rainfall and runoff curve number using the equation:

$$\text{Infiltration} = \text{rainfall } (P) - \text{Runoff } (Q) \qquad [6]$$

The runoff is calculated by the USDA Soil Conservation Service curve number method (USDA Soil Conservation Service, 1972):

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)} \qquad [7]$$

where

$$S = \frac{25400}{CN} - 254 \qquad [8]$$

for units of P, Q and S in mm.

Next the model calculates and uses in subsequent calculations a weighted value for saturated hydraulic conductivity and the difference in the volumetric water contents at saturation and drained upper limit. The weighted values are calculated by:

$$\text{weighted hydc} = \frac{\sum_{1}^{n}\left[hydc_n\right]\left[th_n\right]}{\sum_{1}^{n} th_n} \qquad [9]$$

$$\text{weighted sat-dul} = \frac{\sum_{1}^{n}(sat-dul)_n\,(th)_n}{\sum_{1}^{n} th_n} \qquad [10]$$

where n = layer number for layers from the soil surface to 0.6 m below the pipe depth

hydc = user inputted values of the saturated lateral hydraulic conductivity, l/t, for each soil layer.

sat = user inputted values of the saturated volumetric water content for each layer l/l.

dul = user inputted values of the drained upper limit volumetric water content for each layer, l/l.
th = user inputted thickness of each layer, l.

Steady State Analysis:

SILSPACE calculates the lateral spacing required for subsurface drainage at the design subsurface drainage rate, drrate and subirrigation at the design subirrigation rate, sirate.

The lateral spacing algorithm used by the SILSPACE model is to calculate the spacing using a modification of a steady state equation developed by Hooghoudt and by Ernst (Van Beers, 1976). That method is described in detail by Skaggs, 1980. The modified Hooghoudt equations used are:

$$qd = \frac{8 \cdot k \cdot De \cdot M + 4 \cdot k \cdot M^2}{L^2} \qquad [11]$$

for subsurface drainage and

$$qs = \frac{4 \cdot k \cdot M \left[2 \cdot ho + \frac{ho}{Do} \cdot M \right]}{L^2} \qquad [12]$$

for subirrigation with the terms defined as follows:

L = The design distance between drainage laterals, l. [ldr and lsi]

k = The effective saturated lateral hydraulic conductivity, l/t. [hydc]

M = The difference in water level as measured over the lateral pipe vs. midway between the lateral pipes, l. [sdWTdepthMidpoint-sdWTdepthLateral and siWTdepthMidpoint-siWTdepthLateral]

de = The depth from the center of the lateral pipe to the equivalent impermeable layer, l. [dem]

ho = The distance from the water level over the lateral pipe to the equivalent impermeable layer, l [dwtm-dem].

Do = The distance from the water level over the drain to the actual impermeable barrier, l [dwtm-dbm].

qd = The steady state subsurface drainage coefficient, l/t. [drrate]

qs = The steady state evapotranspiration rate, l/t. [sirate]

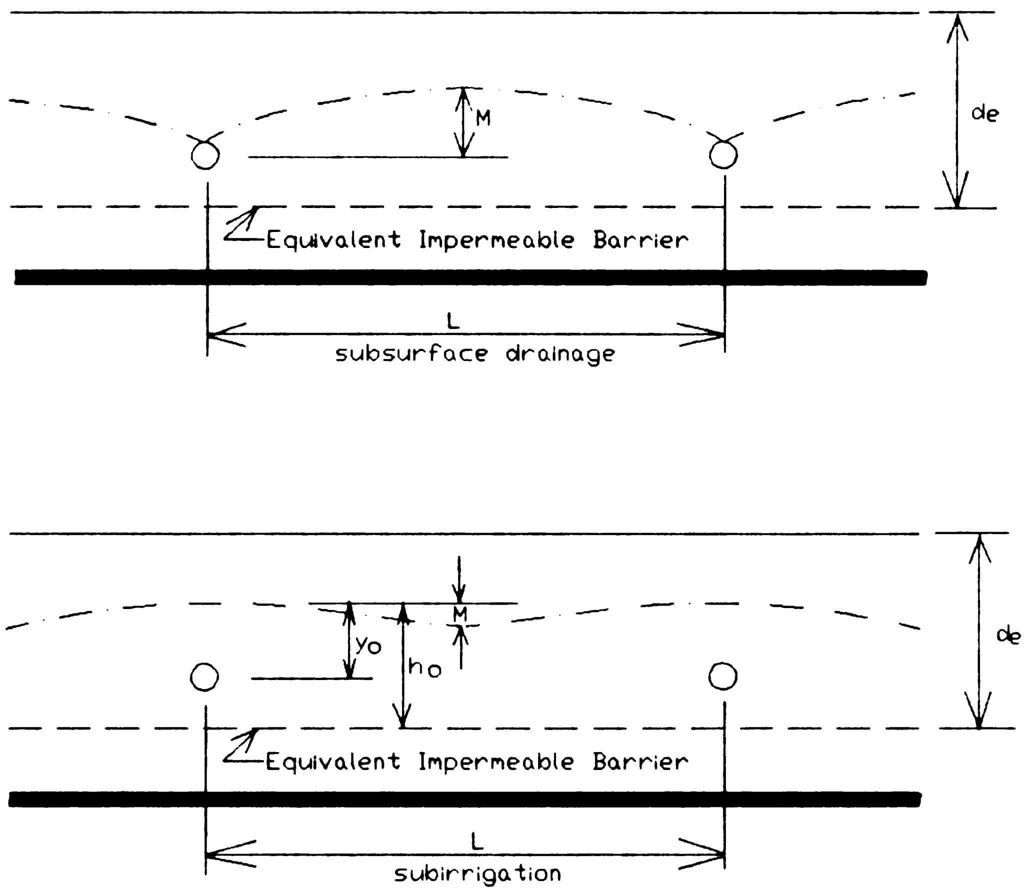


Figure 18. Subsurface drainage/subirrigation lateral spacing design notation.

The equivalent depth, de, to the impermeable layer is introduced to account for losses incurred as water leaves the drain and flows outward during subirrigation mode and for the losses that occur as the flow converges to the drain openings during subsurface drainage. Hooghoudt (Hooghoudt, 1940 and van Schilfgaarde, 1974) evaluated that effect by comparing radial flow near the pipe with flow conforming to the Dupuit-Forchheimer assumptions away from the pipe. Hooghoudt's solutions were formulated by Moody (1966) as follows:

For $0 < d/L < 0.3$

$$de = \frac{d}{1+\frac{d}{L}\left[\frac{8}{\pi}\ln\left[\frac{d}{re}\right]-a\right]} \qquad [13]$$

where

$$a = 3.55-1.6\frac{d}{L}+2\left[\frac{d}{L}\right]^2 \qquad [14]$$

For $d/L > 0.3$

$$de = \frac{L\cdot\pi}{\left[8\cdot\ln\frac{L}{re}-1.15\right]} \qquad [15]$$

in which

L = Lateral Spacing, l. [ldr and lsi]
de = equivalent depth to the barrier, l. [dem]
d = actual depth to the barrier, l. [BarrierDepth]
re = drain tube radius, l. [rem]

The effective drain radius is less than the actual drain radius to account for additional loss of hydraulic head due to convergence of the flow lines resulting from flow entering or leaving the pipe through a finite number of perforations. The values used for re are 3.5, 5.1 and 10.0

mm for pipe diameters 66, 102 and 127 mm respectively (USDA Soil Conservation Service, 1985).

The iterative method of solving for the lateral spacing, L includes calculating the depth to the equivalent impermeable layer.

For both drainage and subirrigation the lateral spacing, L, is solved by iteration using the hydraulic conductivities, depth to barrier, depth to tile and depth to water table values provided by the user.

The module thus computes two lateral spacings - one for subsurface drainage and the second for subirrigation.
The design lateral spacing for further computations is set equal to the lessor of L for drainage and L for subirrigation. The model user has the option of choosing a different design lateral spacing for subsequent calculations.

Transient Analysis:

For the first step in the transient analysis, the model establishes the maximum flow capacity of a lateral pipe using Manning's equation and user inputted values for pipe diameter and grade. In terms of model variable names, Mannings equation is:

$$FullPipeQ = \frac{1}{n}\left[\frac{TileArea}{TilePerimeter}\right]^{\frac{2}{3}}\left[\frac{TileGrade}{100}\right]^{\frac{1}{2}} TileArea \qquad [16]$$

where

FullPipeQ = full pipe flow discharge, l^3/t

n = Manning's roughness coefficient

TileArea = cross-sectional area of the pipe, l^2

TilePerimeter = wetted perimeter of the pipe, l

TileGrade = grade of the pipe, %

The FullPipeQ is put in units of l/t by dividing FullPipeQ by the design lateral spacing and the length of the lateral. The user has the option of reducing FullPipeQ if desired.

Next the rise in the water table from infiltration of the design runoff is calculated. The initial condition is that the system is in the subirrigation mode with the water table at the user inputted depths at the lateral and midway between laterals. The initial water content is assumed to be at 80% of the drained upper limit water content. The rainfall infiltration is assumed to cause 1) an instantaneous leveling of the water table at a depth equal to the average depth at the lateral and depth midway between laterals and 2) an instantaneous rise in the level water table sufficient to store 100% of the infiltration based upon the weighted saturated - .80 * drained upper limit water contents.

Next, the modified Hooghoudt steady state equation is used to calculate the drainage flux (MaxEllipseQ) with the variable m being the difference between the depth to the pipe and the water table depth resulting from the rise in water table because of infiltration.

Calculation of the time for drawdown of the water table from the water table made shallower by infiltration to the design water table depth for steady state subirrigation proceeds in two phases.

For the first phase, the water table is assumed to vary from approximately horizontal to elliptical. At the first phase conclusion 1/2 the vertical height of the ellipse is equal to the difference in the pipe depth and the water table depth immediately following the rise in the water table due to runoff distribution. The horizontal width of the ellipse is equal to the lateral spacing. The ellipse at the conclusion of the first phase is defined by the curve designated WT @ $t_3 > 0$ in Figure 19. The time for phase 1 is calculated by varying the horizontal width of the water table ellipse curve from 0 to L/2 in 1000 steps, integrating the ellipse curve at each step and calculating the time to drain the volume of soil between steps. The time for drainage between steps is calculated by dividing the volume drained between steps (the area between steps times the difference in soil water content at saturation and soil water content at drained upper limit) by the average of the drainage flux between steps. The drainage flux at each step (q) is calculated using the Hooghoudt equation as previously defined. The calculated drainage flux is not allowed to exceed FullPipeQ nor be less than the user inputted drainage coefficient (drrate) + the user inputted subirrigation rate (sirate).

For water table drawdown as shown in Figure 19 the control weir is lowered to drainage lateral depth at time $t_2 = 0$.

For phase 2 flow, the elliptical water table is dropped vertically in 30 mm midpoint increments from the midpoint height of the water table at the end of phase 1 to the midpoint depth of the water table in steady state subirrigation mode before the rainfall event. At each incremental drop, the ellipse curve is integrated and the time to drain the volume of soil within the increment is calculated. The time for drainage between increments is calculated by dividing the volume drained between increments (the area between steps times the difference in soil water content at saturation and soil water content at drained

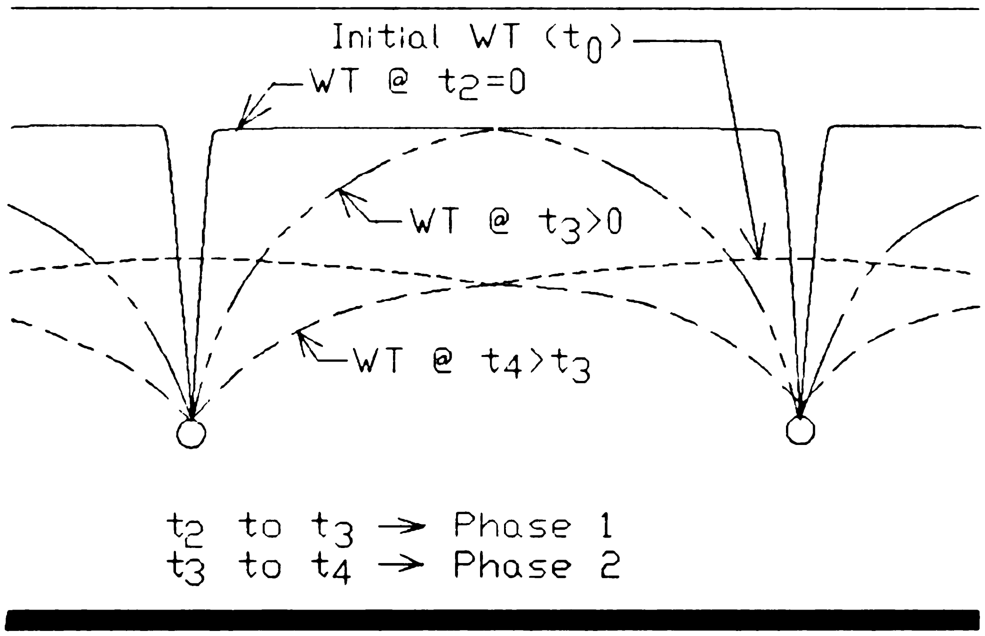


Figure 19. Schematic showing change in water table (WT) with time (t) following a rainfall event through water table drawdown with the subirrigation system initially in a subirrigation mode.

upper limit) by the average of the drainage flux between steps. The drainage flux at each increment is computed by the Hooghoudt equation as previously described.

During the phase 1 and 2 calculation cycles, the time is accumulated and the elapsed time, water table depth at midpoint and drainage flux is shown on the monitor at each step.

Calculated Crop Yield Parameters:

The model uses the rise in water table, number of events and elapsed drawdown time to calculate a crop yield parameter called the wet stress fluctuation index (wfi). The wfi is a parameter that may be used to estimate the mean crop yield that the subirrigation system described by the input data will produce. The wfi quantifies the fluctuation of the water table above the mean water table over the period of time represented by the number of events input by the program user. This provides a water table fluctuation parameter that can be used to estimate yield by comparing the computed wfi to wfi vs. yield relationships obtained through field studies and/or simulation models such as DRAINMOD.

The module computation of wfi is based upon a rise and fall of the water table resulting from the user inputted rainfall as follows:

The wfi parameter is calculated by the following mathematical equation:

$$wfi = \frac{\frac{1}{2}\, dwfi \cdot twfi^2 \cdot events}{TotalTime \cdot 24} \qquad [17]$$

where events = number of rainfall events during the time period of interest (unitless)

TotalTime = Duration of time period of interest (days).

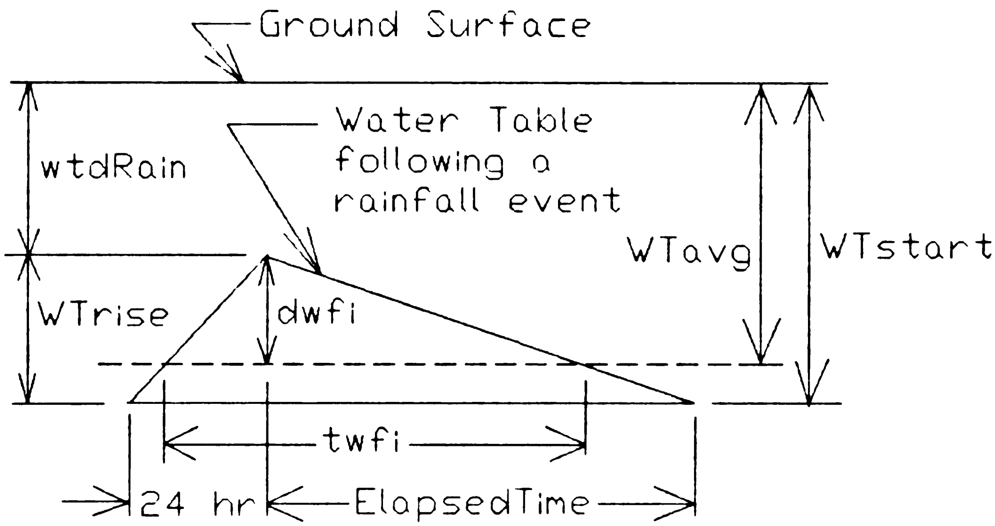


Figure 20. Schematic of assumed water table elevation vs. time following a rainfall event.

$$dwfi = WTavg - wtdRain \qquad [18]$$

$$twfi = \frac{dwfi\left(24 + ElapsedTime\right)}{WTrise} \qquad [19]$$

$$WTrise = WTstart - WtdRain \qquad [20]$$

$$WTavg = \frac{WTstart\ a + \left[wtdRain + \frac{2}{3}WTrise\right] \cdot b}{24 \cdot TotalTime} \qquad [21]$$

$$a = 24 \cdot TotalTime - \left[24 \div ElapsedTime\right] * events \quad [22]$$

$$b = \left[24 \div ElapsedTime\right] * events \quad [23]$$

Results Output:

The following results of the analyses are shown on the monitor along with the input data the results are based upon:

* maximum lateral spacing for subirrigation
* maximum lateral spacing for subsurface drainage
* lateral spacing used for the transient analysis
* time to return to the subirrigation water table depth
* maximum discharge for drawdown
* wfi

The user has the option of obtaining a printout of the input data and results.

Model Evaluation:

The model was evaluated by comparing calculated model subirrigation drawdown durations with observed drawdown durations for selected rainfall events that occurred during the 1986 and 1987 growing seasons at the Bannister site and the 1987 growing season at the St. Johns site. For each selected rainfall event, the differences in saturated and drained upper limit volumetric water contents (sat-dul) were calculated by dividing the observed rainfall by the observed vertical rise in the water table. The sat-dul values used are listed in Table 13. The runoff curve number was calculated by the USDA Soil Conservation Service curve number method (USDA,Soil Conservation Service, 1972). For the Bannister site a curve number of 82 was used (Hydrologic Soil Group C with contoured row crops in good hydrologic condition). The St. Johns site curve number is 75 (Hydrologic Soil Group B with contoured row crops in good hydrologic condition). The input data for each evaluation run simulates the operation of the field systems.

Results:

The results of comparing the observed water table rise and drawdown with simulated rise and drawdown are presented in Table 13.

Discussion:

The comparison of observed and simulated water table rise and water table drawdown shows SILSPACE does a reasonably good job simulating actual field conditions for soils with a

Table 13. Comparison of water table drawdown simulation results to field observation.

SITE	OBS WELL	RAIN mm	WT DEPTH @ START m	OBS DEPTH AFTER RAIN m	CALC sat-dul	OBS DEPTH TO WEIR m	OBS PUMP RATE DURING DRAWDOWN mm/d	OBS TIME TO DRAWDOWN h	SIMUL DEPTH @ START m	SIMUL DEPTH AFTER RAIN m	SIMUL TIME TO DRAWDOWN h
BAN86	WA4M1	29	.62	.42	.15	1.22	0	17	.63	.47	59
BAN86	WB2M2	29	.43	.30	.22	.43	5	43	.42	.31	61
BAN86	WC6M1	29	.78	.42	.08	1.22	8	72	.75	.45	77
BAN86	WE2M1	29	.86	.52	.09	.85	8	72	.86	.58	58
BAN86	WG2M1	29	.37	.29	.36	.37	5	60	.38	.27	60
BAN87	WE4M1	11	1.16	.51	.02	1.19	8	53	1.16	.62	28
SJ87	WB4M2	24	.92	.65	.09	.91	0	31	.93	.70	33
SJ87	WB4M2	23	1.22	.86	.06	1.22	8	58	1.24	.79	50
SJ87	WC4M1	24	.99	.72	.09	.98	0	36	.96	.73	33
SJ87	WC4M1	23	1.14	.78	.06	1.13	8	75	1.12	.66	51

loamy clay texture and with a loamy sand texture. The differences in simulated and observed results are likely to be, in part, due to differences in hydraulic conductivity, differences in runoff curve number, differences in pipe flow limitations and approximations used for the simulation algorithms.

The SILSPACE module demonstrates dramatically that the balance between the various components must be considered in the design process. It is evident that reducing lateral spacing to decrease the time required to return the water table to the desired depth following a rainfall event may not be effective if the hydraulic capacity of the submains and mains is not increased.

The runs made with the module also show that the time to lower the water table is dependent upon the weir setting before and after the rainfall event.

Finally, the module shows that the difference between depth to the water table at the lateral and at the midpoint between laterals greatly affects the time required to return the water table to the design depth following a precipitation event.

The data required as input for the module is fairly easy to obtain. The lateral saturated hydraulic conductivity may be determined in situ (by auger hole and/or velocity permeameter) or by laboratory analysis on undisturbed cores. The depth to the barrier can be determined by soil borings or excavation of backhoe pits at the site. The volumetric water contents at saturation and drained upper limit can be easily determined in situ or in the laboratory on undisturbed cores. Historic daily rainfall records from location near the sites are readily available in the United States and most of the developed world.

The wfi parameter is analogous to the SEW_{30} parameter (Wesseling, 1974 and Bouwer, 1974) as originally defined by Sieben (1964) to evaluate the effect of fluctuating water tables on cereal crop production. The module uses the wfi concept instead of SEW_{30} for two reasons. A meaningful value for SEW_{30} is not possible using a 50% probability rainfall event projected over the growing season. Also, the operational concept of subirrigation is to establish a constant water table at a depth that will provide the water needs of the plant. Under that situation, the plant will develop a root system as needed to utilize the ground water via capillarity from the water table. The performance criteria for the subirrigation system thus is "How well is the system maintaining the water table at the design depth?" The wfi parameter is a quantitative evaluation of how well the system maintains a constant water table. The wfi parameter can be determined from research data of water table depth or elevations with time as well as computer simulations that provide water table depth with time as an output. The field research shows crop yield can be related to the wfi parameter. It is expected those relationships are mostly independent of soil and climate (as is SEW_{30}). This allows system designers to apply the crop yield results from limited field studies and/or computer simulations to a broad range of soil and climatic conditions through application of the SIDESIGN computer model.

SIMAIN DESCRIPTION

The SIMAIN module assists the system designer determine the needed diameter for the submain and main collector pipes. The user enters the system design drainage coefficient, subirrigation rate, lateral spacing and the grade of mains and submains. The program uses Manning's equation

$$FullPipeQ = \frac{1}{n}\left[\frac{TileArea}{TilePerimeter}\right]^{\frac{2}{3}}\left[\frac{TileGrade}{100}\right]^{\frac{1}{2}} TileArea \qquad [24]$$

where

FullPipeQ = full pipe flow discharge, l^3/t

n = Manning's roughness coefficient

TileArea = cross-sectional area of the pipe, l^2

TilePerimeter = wetted perimeter of the pipe, l

TileGrade = grade of the pipe, %

to compute the maximum length of pipe and drainage area capable of providing pipe flow discharge at the design drainage and subirrigation rates for the lateral spacing and for pipe diameters from 102 mm through 457 mm.

Following the calculations the program shows the results on the monitor. The user is given the option to get a printout of the results and/or run the module again with different input data.

SIECON DESCRIPTION

A water table management system to maximize the economic efficiency of plant biomass production will involve tradeoffs. Reducing pipe size and/or lateral spacing will reduce system cost but will also reduce the ability of the system operator to maintain the ideal water table location. Rainfall events may increase plant stress from excess soil water which may reduce plant biomass production. Likewise deficit soil water conditions with plant biomass production reductions may result from the system operation not keeping up with crop water needs.

To evaluate field crop vs. water table depth and fluctuation relationships in economic terms, the economic analysis computer module (SIECON) was developed. The module compares water table management system annual benefit to annual cost.

Module Algorithm:

A properly designed, installed and operated subirrigation system will provide increased agricultural yield most years. It has been shown that system variables such as lateral spacing and depth, capacity of the mains and submains, irrigation water supply capability, etc. all affect the magnitude of the yield increase. Likewise, those same system variables establish the system cost - installation cost, operation cost and replacement cost. Generally, an increased yield is accompanied by an increase in system cost.

Alternative levels of subirrigation system capability are mutually exclusive alternatives (Riggs and West, 1986). In other words, the selection is limited to the do-nothing option, or A, or B. To compare alternatives, the net annual equivalent value (ANEV) of each alternative is calculated and the alternatives ranked in order of net annual equivalent value (Potter, 1985). The positive contributors to the net annual equivalent value of an alternative consist of yield multiplied by (market value minus production cost) for the crop. The negative contributors consist of the system installation cost, the system operation and maintenance cost and the salvage value of the system all converted to an annual cost using an interest rate equal to a minimum attractive rate of return (MARR).

Variables such as future costs of production, market value, inflation, tax benefit and/or cost, value of land, etc. are not included in the analysis. Estimation of these variables are highly judgmental and their inclusion would not improve the accuracy of the comparisons.

A detailed description of each variable used in the economic analysis is as follows:

Installed Cost of the System (P):

The installed cost of the system (P) is the sum of:

- the unit cost of the main times the total length of main
- the unit cost of laterals times the total length of laterals
- the unit cost of head control stands times the number of zones
- the unit cost of the water supply line times the total length of the water supply lines
- the cost of the well
- the cost of the pump
- the cost of the motor or engine
- the cost of providing energy to the site

To convert P to an annual cost, the following equation is used:

$$A = \frac{P \cdot i \cdot (1+i)^n}{(1+i)^n - 1} \qquad [25]$$

where

P = installation cost

i = minimum attractive rate of return (%)

n = system life before replacement (y)

Total Annual System Cost (ASC):

The total annual system cost (ASC) is the sum of A and the annual cost of operating and maintaining the

system.

The SIECON module calculates the annual system benefit using user inputted values for with system and without system yield, production costs and product prices.

Annual System Income (ASI):

The annual system income (ASI) is equal to:

income from field w/ system - income from field w/o system [26]

where income from field w/ system is equal to:

field size*yield w/system*product price - field size*production cost w/ system [27]

and income from field w/o system is equal to:

field size*yield w/o system*product price - field size*production cost w/o system [28]

Benefit/Cost Ratio:

The Benefit/Cost Ratio then is annual system income divided by the annual system cost (ASI/ASC).

Data Input:

The module user has the option of providing the input data interactively or by specifying a disk file. For the disk file the input data is on a single line, comma separated, in the following order.

* estimated installation cost of the system ($)
* estimated cost of operating and maintaining the

system ($)

* expected life of the system (yr)
* minimum attractive rate of return (%)
* field size (area)
* estimated yield without the system (vol/unit area)
* estimated yield with the system (vol/unit area)
* production cost without the system ($/unit area)
* production cost with the system ($/unit area)
* expected market value of the crop ($/unit vol)

The module calculates and prints:

* total installation cost
* total annual system cost
* total annual increase in income due to system
* benefit/cost ratio

Discussion:

The design process for water table management systems must consider economics. The computer module SIECON provides a relatively easy way to relate economics to other aspects of the design process.

The installation cost of the system is the estimated cost of the system installed. The annual operation and maintenance cost is an estimate of the value of the time and expense to keep the system in good repair and operating. The rate of interest should be the rate considered to be the minimum acceptable rate of return from the investment in the water table management system. That interest should be at least as high as the return available on guaranteed investment opportunities. The production cost input is an estimate of the cost of seed, fertilizer, herbicide, tractor operation costs, combine operation costs for the field and crop on a unit area basis. The annual yield without the system comes from knowledge of past yields. The annual yield with the system is based upon the performance of the system in terms of water table fluctuation vs. yield.

The before tax benefit/cost ratio calculated by the module can be interpreted as follows:

> The number 1 is the breakeven point.
>
> Any number greater than 1 shows the system will make money.
>
> The alternative with the largest benefit/cost ratio over 1 is the best alternative economically.

The SIECON module does not include depreciation, taxes, value of land, etc. which may also affect the economics of choosing an alternative. The before tax benefit/cost ratio is a summary of the economic analysis and is intended to be helpful in selecting an alternative.

EXAMPLE APPLICATION

The SIDESIGN model can be used to relate operational characteristics of a water table management system or system alternatives to water table depth and water table fluctuation parameters by the following procedure:

Step 1. Using historic growing season rainfall records from near the site location, run the SIRAIN module to determine the growing season rainfall amounts for the 2 and 10 year recurrence intervals and the 2 year recurrence interval number of rainfall events per season.

Step 2. Apply the SIRAIN results to the SILSPACE module to obtain drawdown times and wfi parameters for a series of subirrigation system design alternatives (alternate lateral spacing and drainage rates).

Step 3. Use the SIMAIN module to determine main sizes for each of the Step 2 alternatives.

Step 4. For each alternative, estimate the system installation cost.

Step 5. For each alternative, use the drawdown and wfi results from Step 2 to estimate the probable yield.

Step 6. Use the SIECON module for each design alternative to estimate the benefit/cost ratio for each system alternative.

Step 7. Select the system alternative with the greatest benefit/cost ratio.

An example of the application of the SIDESIGN model is provided as Appendix G.

CONCLUSIONS

SILSPACE Module:

1. The SILSPACE module does a reasonably good job of simulating the performance of a water table management system in the subirrigation mode using input data that is relatively easy to obtain.

2. The module provides water table management system designers with a procedure to design water table management systems that will meet current standards for subsurface drainage, will provide irrigation water to the root zone at a rate consistent with the crop needs and will limit fluctuation of the water table within limits established by the system designer.

SIECON Module:

1. The SIECON module includes the economic factors needed to evaluate the annual cost of a water table management system design alternative and the average annual increase in income estimated to result from the alternative.

2. The SIECON module, in conjunction with SILSPACE and yield vs. water table depth/fluctuation parameters relations provides the water table management system designer with the tools needed to design water table management systems that maximize the economic efficiency of plant biomass production.

SIDESIGN Model:

1. The model is operational on micro-processor based computers, is interactive and does not require substantial calculation time even with minimal computational resources.

2. Application of the model shows that:

   a. the management of the water table fluctuation is important to corn and soybean production and needs to be considered in the design of subirrigation systems.

   b. additional research is needed to establish water table depth/fluctuation vs yield relationships to design and operate subirrigation systems.

CONCLUSIONS

1. The management of the water table fluctuation is important to corn and soybean production and needs to be considered in the design of water table management systems.

2. The wet/dry stress fluctuation index appears to be a valid method of evaluating water table fluctuation research results that is applicable to water table management system design.

3. Additional research is needed to establish water table depth/fluctuation vs. yield relationships to design and operate water table management systems that maximize the economic efficiency of plant biomass production.

4. Additional research is needed to determine the effect a controlled receding water table during the growing season has on plant biomass production.

5. There is a need to continue field size study of the water table fluctuation effects on yield for a variety of soil conditions, crops and climatic areas. Along with the field size studies, a water table management research facility that allows for replication and reduces non-treatment variables that affect plant biomass production is needed to better define the water table depth/fluctuation vs. yield relationships.

6. The design procedure developed as a part of this study allows for efficient system design that is based upon easily obtainable field and climatic data and includes water table depth and fluctuation as design parameters.

7. The water table management system design computer program SIDESIGN provides designers the opportunity to develop system designs based upon site soil hydraulic properties, water table management capabilities and economic efficiency.

APPENDIX A

BANNISTER SITE SOIL DATA

APPENDIX A

CLASSIFICATION: ZIGENFUSS; FINE-LOAMY, MIXED, NONACID, MESIC MOLLIC HAPLAQUEPT

SAMPLE NO	DEPTH (CM)	HORIZON	TOTAL CLAY LT .002	TOTAL SILT .002 -.05	TOTAL SAND .05 -2	CLAY FINE LT .0002	CLAY CO3 LT .002	SILT FINE .002 -.02	SILT COARSE .02 -.05	SAND VF .05 -.10	SAND F .10 -.25	SAND M .25 -.50	SAND C .5 -1	SAND VC 1 -2	COARSE FRACTIONS (MM) WEIGHT 2 -5	WEIGHT 5 -20	WEIGHT 20 -75	.1- 75	(>2MM) WT PCT OF WHOLE SOIL
			<- PCT OF <2MM (3a1)											->	<- PCT OF <75MM(3B1)			->	
85P3482S	0- 23	AP	24.3	47.9	27.8			29.3	18.6	5.7	12.5	7.4	1.6	0.6	2	--	--	24	2
85P3483S	23- 38	BG1	30.3	39.4	30.3			27.5	11.9	6.1	14.3	7.4	1.7	0.8	1	1	--	26	2
85P3484S	38- 61	BG2	28.0	33.6	38.4			22.1	11.5	7.4	17.9	9.7	2.3	1.1	5	--	--	34	5
85P3485S	61- 92	BG3	33.0	36.3	30.7			25.7	10.6	6.0	14.6	7.8	1.6	1.3	2	2	--	28	4
85P3486S	92-112	CG1	31.6	36.8	31.6			25.6	11.2	6.4	14.5	7.8	1.6	1.3	2	2	--	28	4
85P3487S	112-160	CG2	29.7	39.1	31.2			26.7	12.5	6.1	13.6	7.5	2.4	1.6	2	3	1	30	6

DEPTH (CM)	ORGN C PCT	(-RATIO/CLAY-) CEC	15 BAR	(BULK DENSITY) 1/3 BAR (- -G/CC- -)	OVEN DRY	COLE WHOLE SOIL CM/CM	(-WATER CONTENT-) 1/10 BAR (- PCT OF <2MM -)	1/3 BAR	15 BAR	WRD WHOLE SOIL CM/CM	(- - - CLAY/MINERALOGY - RELATIVE AMOUNTS - - -) (<.002MM)			
0- 23	1.90	0.61	0.44	1.62	1.76	0.028	23.3	22.2	10.6	0.19	KK 3	MI 3	VM 2	VR 1
23- 38	0.78	0.44	0.40	1.65	1.79	0.027	21.3	20.3	12.2	0.13	KK 3	MI 3	VM 2	VR 1
38- 61	0.42	0.41	0.39	1.68	1.84	0.030	21.5	20.4	10.9	0.15	KK 3	MI 3	VM 3	GE 1
61- 92	0.38	0.35	0.40	1.68	1.85	0.032	21.3	20.6	13.3	0.12	MI 3	KK 3	VM 2	GE 1
92-112	0.32	0.34	0.42	1.69	1.84	0.028	19.8	19.1	13.3	0.10	MI 3	KK 3	VM 2	GE 1
112-160	0.41	0.34	0.42	1.63	1.81	0.034	21.4	21.0	12.5	0.13	MI 3	KK 3	VM 2	GE 1

AVERAGES, DEPTH 25-100: PCT CLAY 31 PCT .1-75MM 29

ANALYSIS: S= ALL ON SIEVED <2MM BASIS

MINERALOGY: KIND OF MINERAL KK KAOLINITE MI MICA VM VERM-MICA VR VERMICULITE GE GOETHITE
RELATIVE AMOUNT 6 INDETERMINATE 5 DOMINIATE 4 ABUNDANT 3 MODERATE 2 SMALL 1 TRACE

NOTE: THIS PEDON IS A TAXIJUNCT TO THE ZIEGENFUSS SERIES. IT HAS LESS THAN 35% CLAY IN THE CONTROL SECTION

APPENDIX B

ST. JOHNS SITE SOIL DATA

APPENDIX B

CLASSIFICATION: WASEPI; COARSE-LOAMY, MIXED, MESIC AQUOLLIC HAPLUDALF

SAMPLE NO	DEPTH (CM)	HORIZON	(- - -TOTAL- - -) CLAY LT .002	SILT .002 -.05	SAND .05 -2	(- CLAY -) FINE LT .0002	CO3 LT .002	(- -SILT- -) FINE .002 -.02	COARSE .02 -.05	(- - - - - - - -SAND- - - - - - -) VF .05 -.10	F .10 -.25	M .25 -.50	C .5 -1	VC 1 -2	(- COARSE FRACTIONS(MM) -) --------WEIGHT-------- 2 -5	5 -20	20 -75	.1- 75	(>2MM) WT PCT OF WHOLE SOIL
			<- - - - - - - - - - - - - PCT OF <2MM (3a1)											- - - - - - - - - - - - - - - - - ->	(<- PCT OF <75MM(3B1)			->	SOIL
86P5548S	0- 23	AP	10.3	16.2	73.5			9.2	7.0	8.3	27.2	29.4	6.8	1.8	3	3	--	67	6
86P5549S	23- 48	BT1	13.8	19.3	66.9			11.2	8.1	8.5	29.9	21.1	4.9	2.5	3	3	--	61	6
86P5550S	48- 71	BT2	10.7	13.2	76.1			7.3	5.9	7.4	30.4	28.1	6.8	3.4	4	5	1	72	10
86P5551S	71-100	BC	7.8	11.9	80.3			6.1	5.8	6.3	19.8	37.3	12.8	4.1	5	8	--	77	13
86P5552S	100-150	2CG	1.9	4.1	94.0			1.8	2.3	1.9	26.1	56.3	7.4	2.3	3	6	4	93	13

DEPTH (CM)	ORGN C PCT	(-RATIO/CLAY-) CEC	15 BAR	(BULK DENSITY) 1/3 BAR	OVEN DRY (- -G/CC- -)	COLE WHOLE SOIL CM/CM	(-WATER CONTENT-) 1/10 BAR	1/3 BAR	15 BAR (- PCT OF <2MM -)	WRD WHOLE SOIL CM/CM	(- - - CLAY/MINERALOGY - RELATIVE AMOUNTS - - -) (<.002MM)				
0- 23	1.88	1.24	0.64						6.6		MT 3	KK 2	MI 2	CL 1	QZ 1
23- 48	0.26	0.75	0.49						6.7		MT 3	KK 3	MI 3	VR 2	GE 1
48- 71	0.30	0.56	0.46						4.9		MT 3	KK 3	MI 3	VR 2	GE 1
71-100	0.32	0.50	0.53						4.1		KK 3	MI 3	MT 2	VR 2	GE 2
100-150	0.10	0.26	0.47						0.9		KK 3	MI 2	VR 1	MT 1	GE 1

MINERAL INTERPRETATION:

MT montmorillinite KK kaolinite MI mica CL chlorine QZ quartz VR vermiculite
GE goethite GI gibbsite

RELATIVE PEAK SIZE: 5 Very Large 4 Large 3 Medium 2 Small 1 Very Small 6 No Peaks

APPENDIX C

WATER TABLE ELEVATION VS. TIME PLOTS

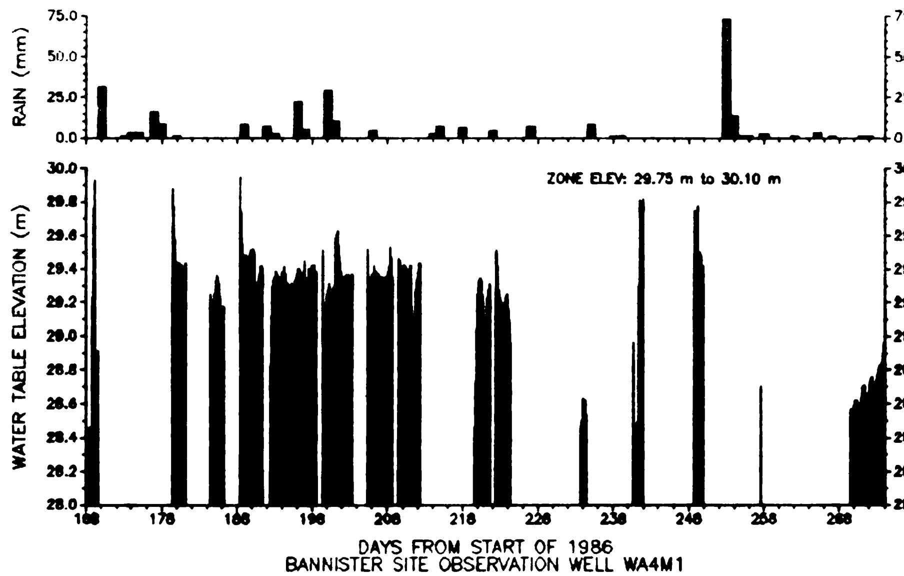


Figure C1. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WA4M1 for 1986 growing season at the Bannister site.

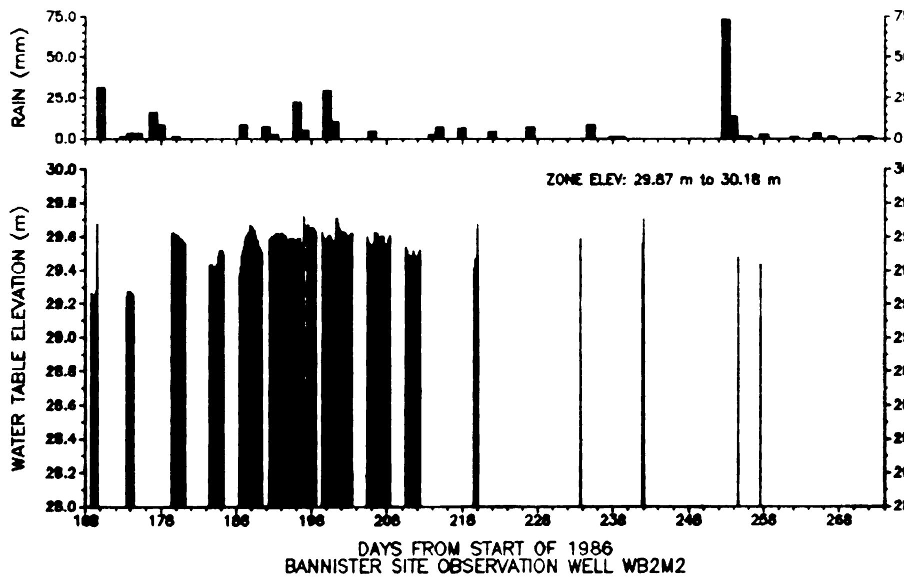


Figure C2. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WB2M2 for 1986 growing season at the Bannister site.

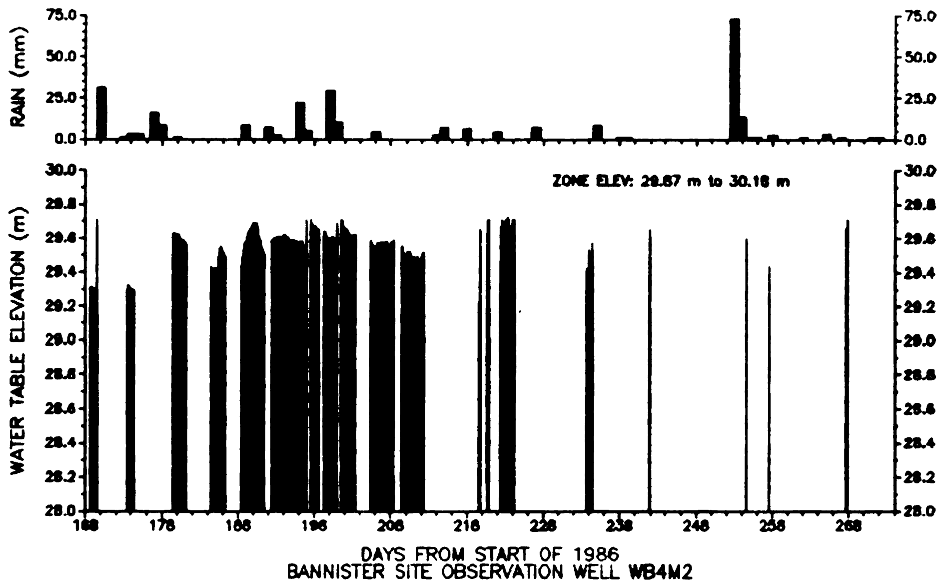


Figure C3. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WB4M2 for 1986 growing season at the Bannister site.

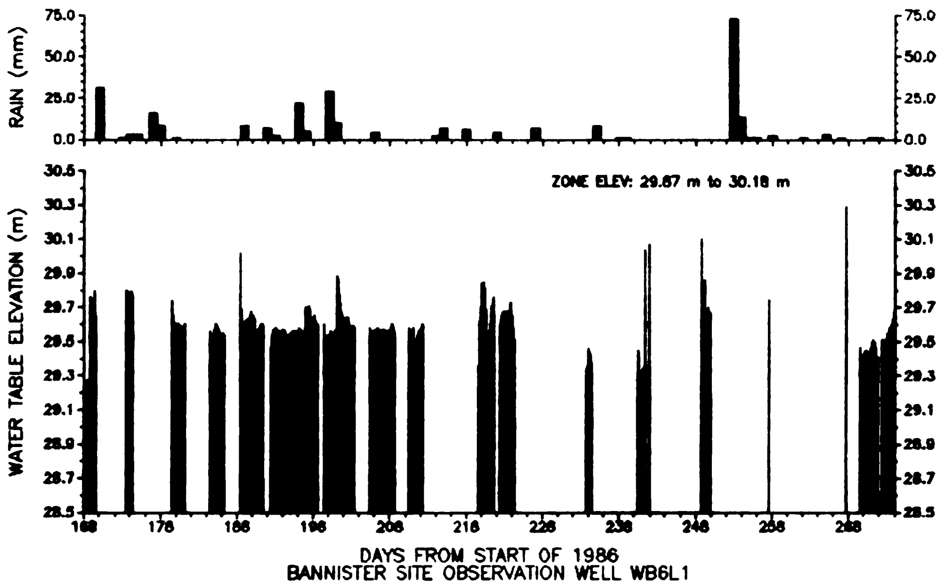


Figure C4. Water table elevation (m) and raqinfall (mm) vs. time (days) for observation well WB6L1 for 1986 growing season at the Bannister site.

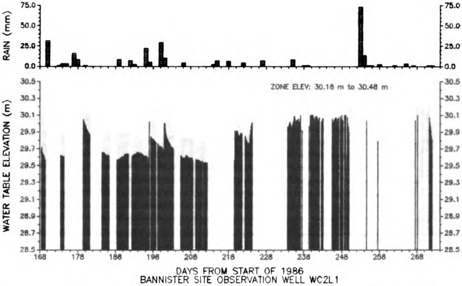


Figure C5. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WC2L1 for 1986 growing season at the Bannister site.

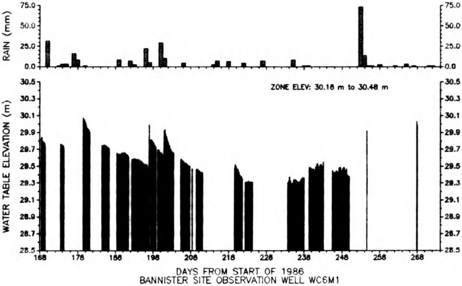


Figure C6. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WC6M1 for 1986 growing season at the Bannister site.

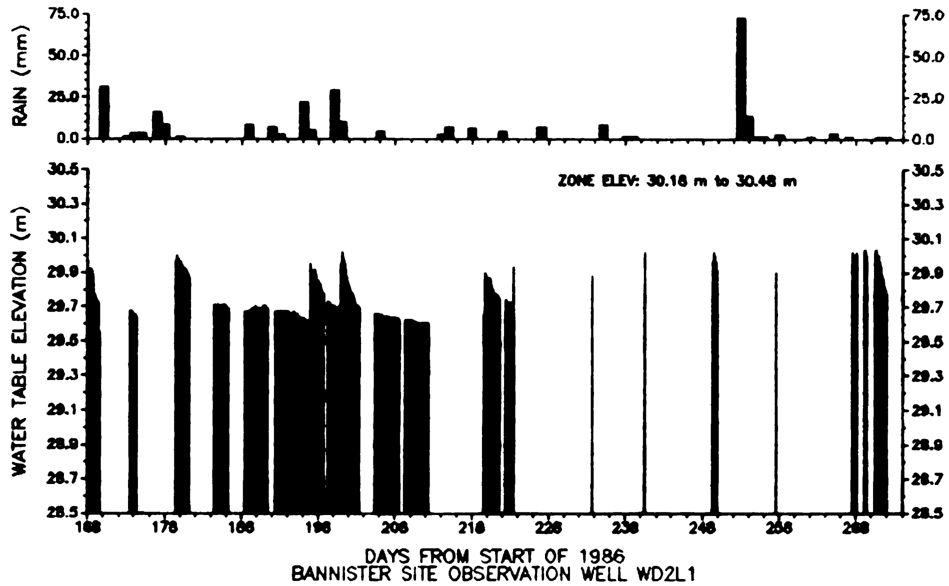


Figure C7. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WD2L1 for 1986 growing season at the Bannister site.

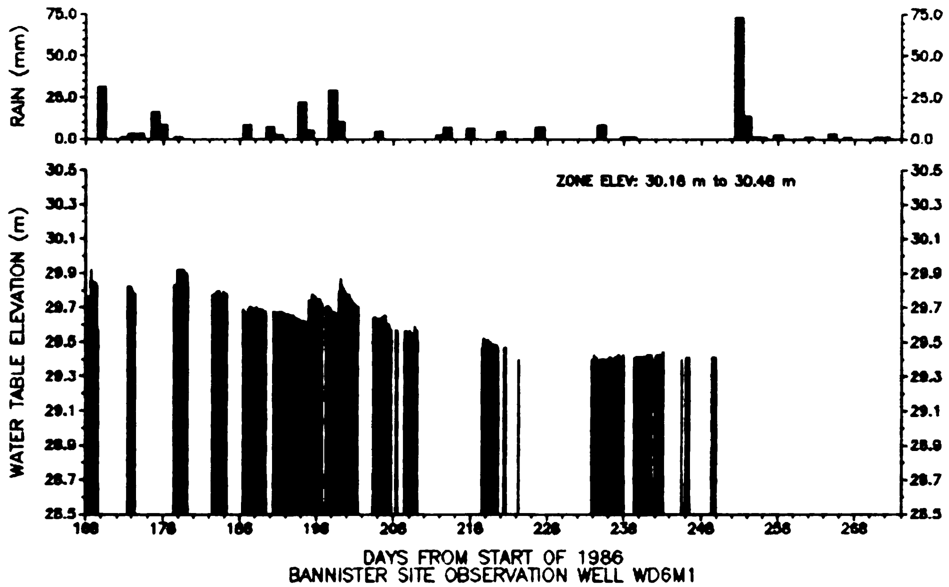


Figure C8. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WD6M1 for 1986 growing season at the Bannister site.

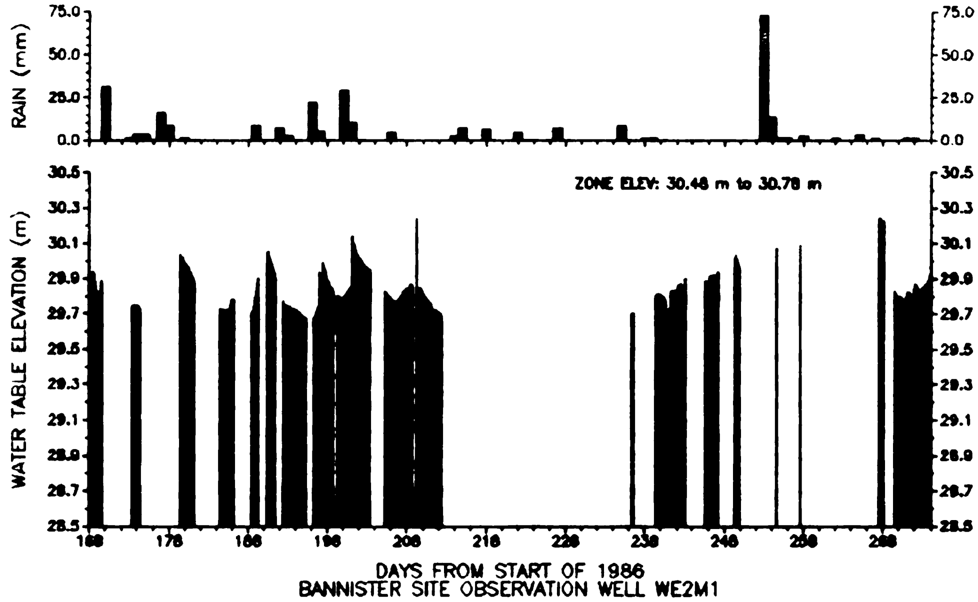


Figure C9. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WE2M1 for 1986 growing season at the Bannister site.

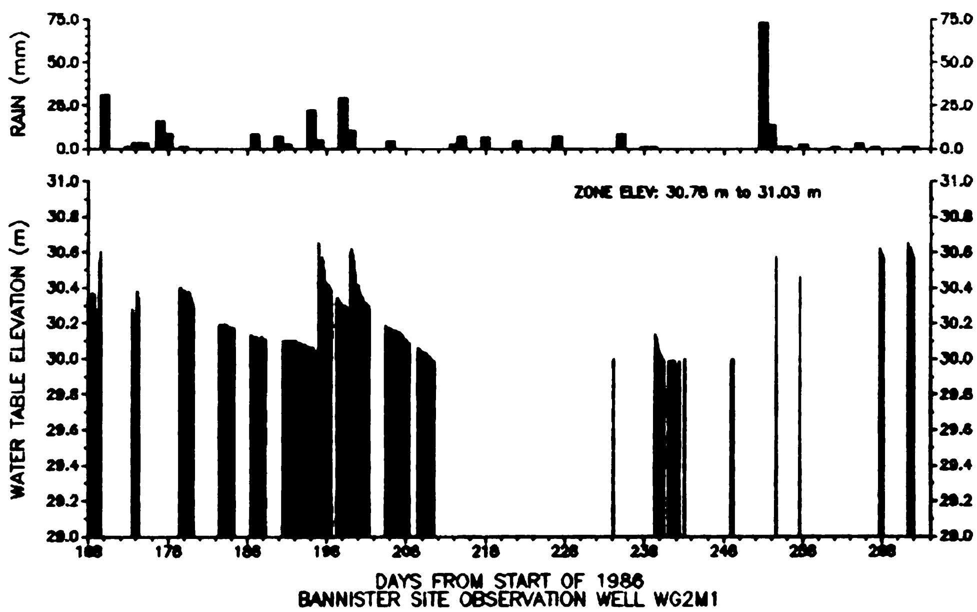


Figure C10. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WG2M1 for 1986 growing season at the Bannister site.

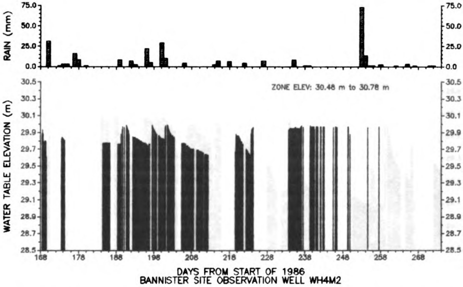


Figure C11. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WH4M2 for 1986 growing season at the Bannister site.

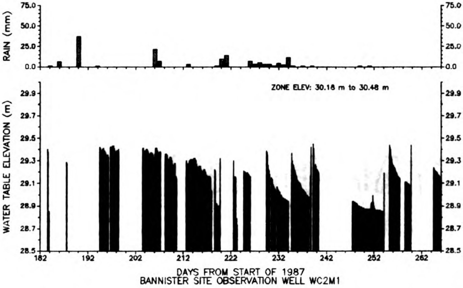


Figure C12. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WC2M1 for 1987 growing season at the Bannister site.

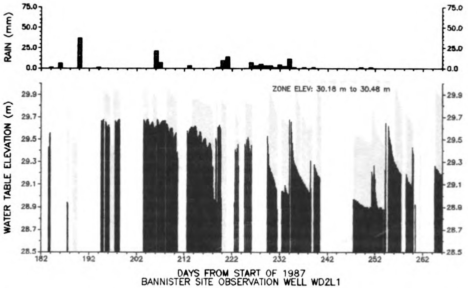


Figure C13. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WD2L1 for 1987 growing season at the Bannister site.

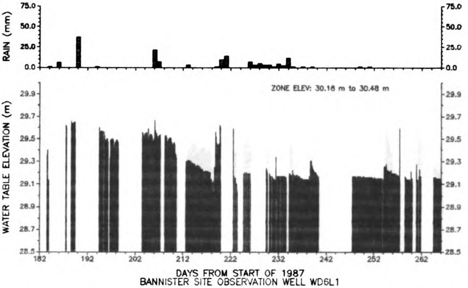


Figure C14. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WD6L1 for 1987 growing season at the Bannister site.

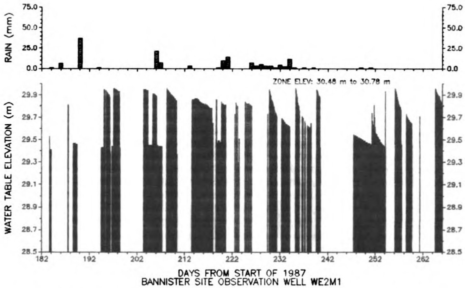


Figure C15. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WE2M1 for 1987 growing season at the Bannister site.

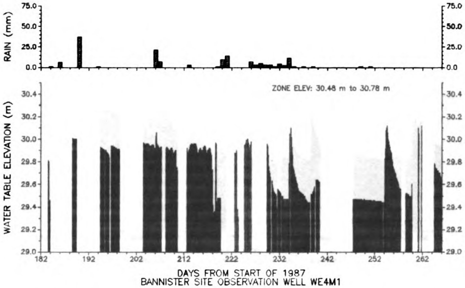


Figure C16. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WE4M1 for 1987 growing season at the Bannister site.

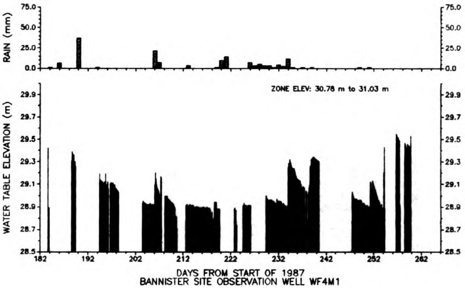


Figure C17. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WF4M1 for 1987 growing season at the Bannister site.

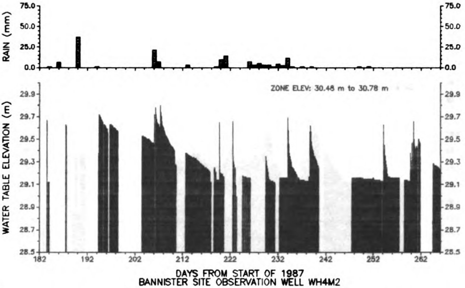


Figure C18. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WH4M2 for 1987 growing season at the Bannister site.

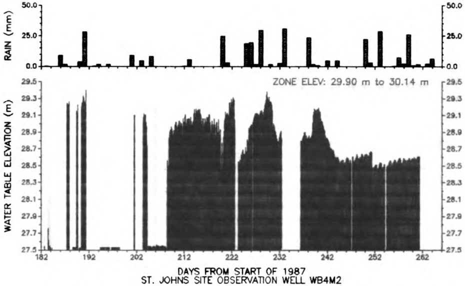


Figure C19. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WB4M2 for 1987 growing season at the St. Johns site.

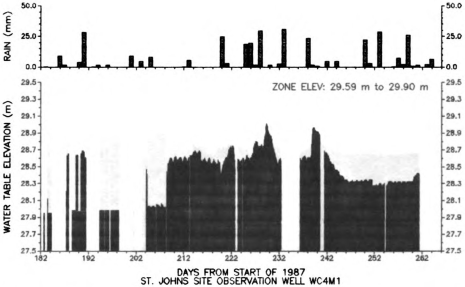
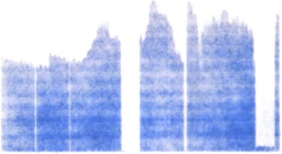
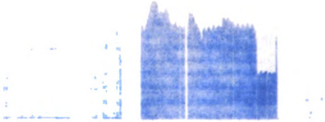


Figure C20. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WC4M1 for 1987 growing season at the St. Johns site.





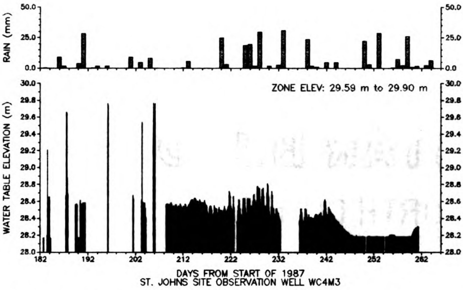


Figure C21. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WC4M3 for 1987 growing season at the St. Johns site.

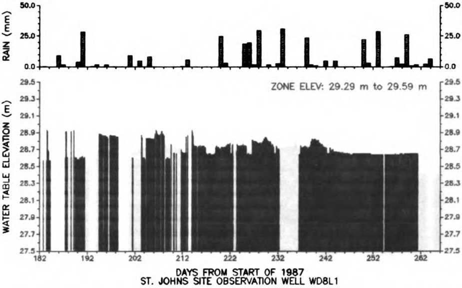
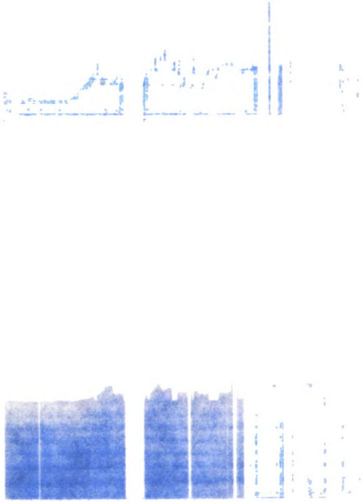


Figure C22. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WD8L1 for 1987 growing season at the St. Johns site.



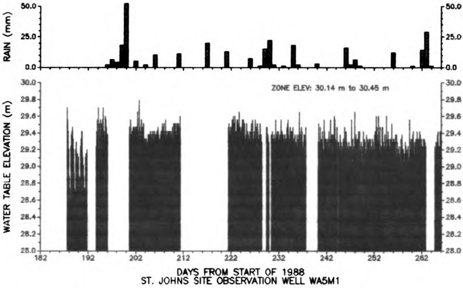


Figure C23. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WA5M1 for 1988 growing season at the St. Johns site.

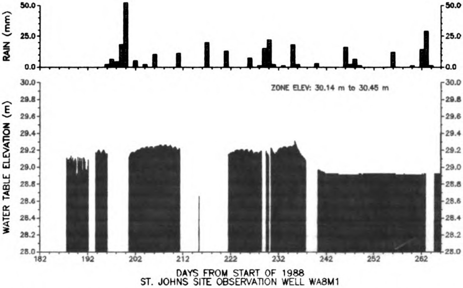
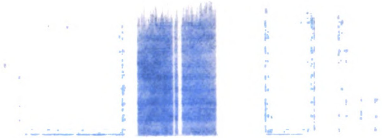
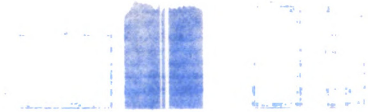


Figure C24. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WA5M1 for 1988 growing season at the St. Johns site.





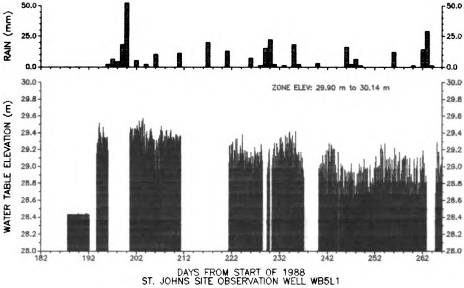


Figure C25. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WB5L1 for 1988 growing season at the St. Johns site.

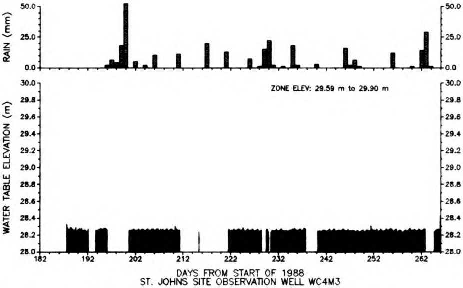


Figure C26. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WC4M3 for 1988 growing season at the St. Johns site.

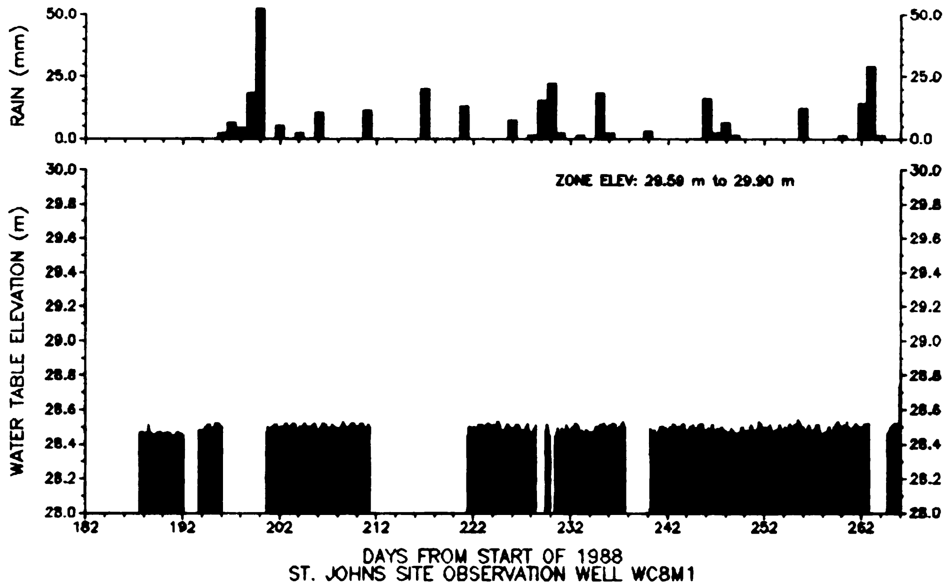


Figure C27. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WC8M1 for 1988 growing season at the St. Johns site.

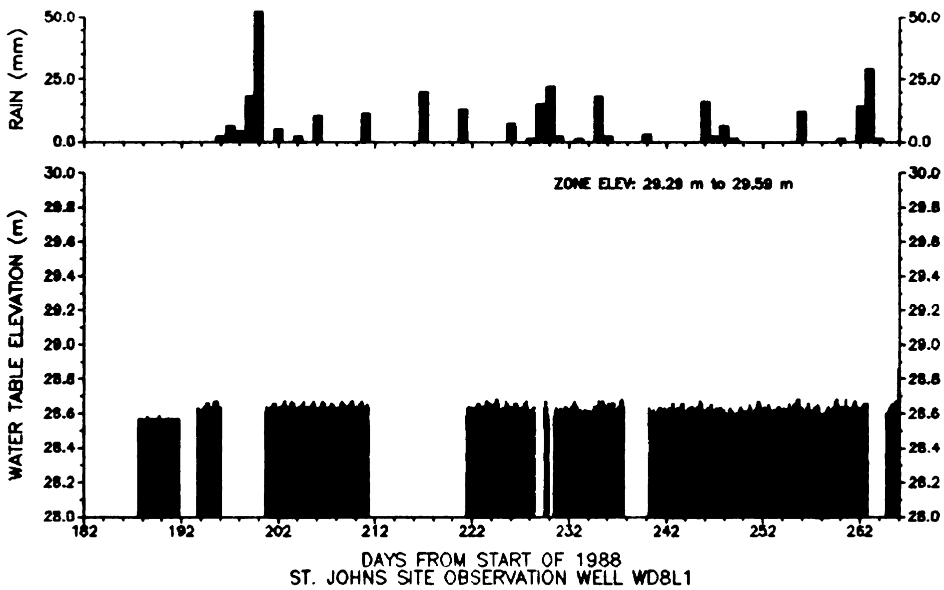


Figure C28. Water table elevation (m) and rainfall (mm) vs. time (days) for observation well WD8L1 for 1988 growing season at the St. Johns site.

APPENDIX D

FIELD DATA SCATTER PLOTS

```
    -   A                   A
    -                                           A2
 80+
    -   A3                  A
    -                       B
    -                                           A
    -   B2
 60+    B                   B                   B
    -
    -                       B                   B2
    -   B
     ------+---------+---------+------
          8.0       12.0      16.0
```

A = cyield vs. spacing   B = syield vs. spacing

Figure D1. Scatter plot of relative corn yield (cyield,%,A) and relatvie soybean yield (syield,%,B) vs. spacing of underground pipe system laterals (spacing,m) during the 1986 growing season at the Bannister site.

```
    -      A                                    A
    -   A                                   A
 80+
    -              A  A                       A A
    -                                           B
    -                               A
    -              B  B
 60+                                B   B       B
    -
    -   B B                             B
    -      B
     ----+---------+---------+--------
       0.48       0.60      0.72
```

A = cyield vs. swtd   B = syield vs. swtd

Figure D2. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. mean depth to the water table (swtd,m) during the 1986 growing season at the Bannister site.

```
  -    A               A
  -                 A  A
80+
  -      A                 A  A  A
  -                    B
  -          A
  -                        B     B
60+      B     B             B
  -
  -       B          B  B
  -    B
    ----+---------+---------+--------
       30        45        60
```

A = cyield vs. stimeb   B = syield vs. stimeb

Figure D3. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was below the mean water table depth (stimeb,%) during the 1986 growing season at the Bannister site.

```
  -              A               A
  -              A2
80+
  -     A  A   A                 A
  -              B
  -                        A
  -     B      B
60+          B             B     B
  -
  -              B2           B
  -                              B
    ----+---------+---------+--------
       30        45        60
```

A = cyield vs. stimea   B = syield vs. stimea

Figure D4. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was above the mean water table depth (stimea,%) during the 1986 growing season at the Bannister site.

```
  - A      A
  -        A              A
80+
  -               A   A    A      A
  -        B
  -            A
  -               B               B
60+            B      B         B
  -
  -  B     B              B
  - B
    ----+---------+---------+--------
       15        30        45
```

A = cyield vs. sdfi   B = syield vs. sdfi

Figure D5. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation dry stress index (sdfi,m*hr/hr) for the 1986 growing season at the Bannister site.

```
  -     A A
  -     A       A
80+
  -     A   A     A               A
  -     B
  -              A
  -     B         B
60+           B  B                B
  -
  -     B B     B
  -       B
    --------+---------+---------+----
           25        50        75
```

A = cyield vs. swfi   B = syield vs. swfi

Figure D6. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation wety stress index (swfi,m*hr/hr) for the 1986 growing season at the Bannister site.

```
  -     A                         A
  -     A                 A
80+
  -                  AA A        A
  -                               B
  -                   A
  -                  B  B
60+                   B2    B
  -
  -     B2                B
  -     B
    ----+---------+---------+--------
     0.45      0.60      0.75
```

A = cyield vs. jwtd   B = syield vs. jwtd

Figure D7. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. mean depth to the water table (jwtd,m) during July, 1986 at the Bannister site.

```
  -  A                  A
  -                       A2
80+
  -       A                     AA A
  -                     B
  -                      A
  -                             BB
60+       B              B        B
  -
  -    B                  B2
  -  B
    --------+---------+---------+----
           40        50        60
```

A = cyield vs. jtimeb   B = syield vs. jtimeb

Figure D8. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was below the mean water table depth (jtimeb,%) during July, 1986 at the Bannister site.

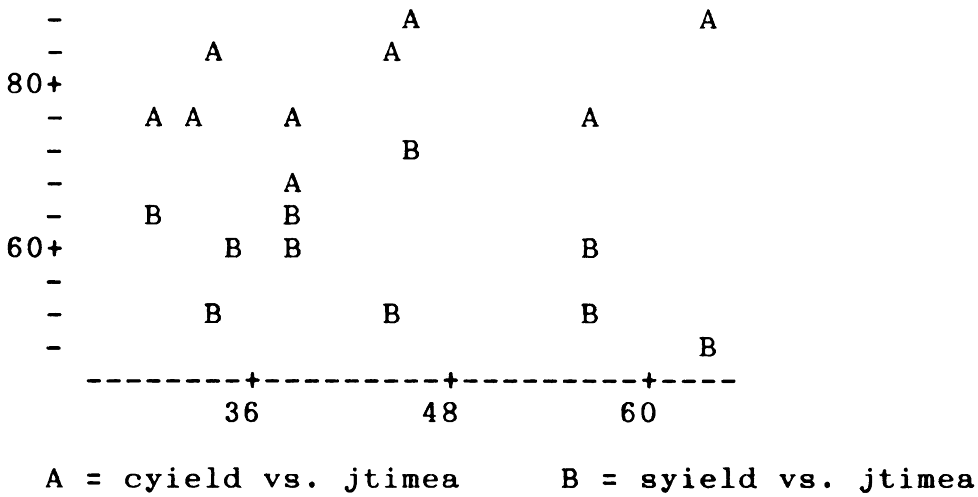


Figure D9. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was above the mean water table depth (jtimea,%) during July, 1986 at the Bannister site.

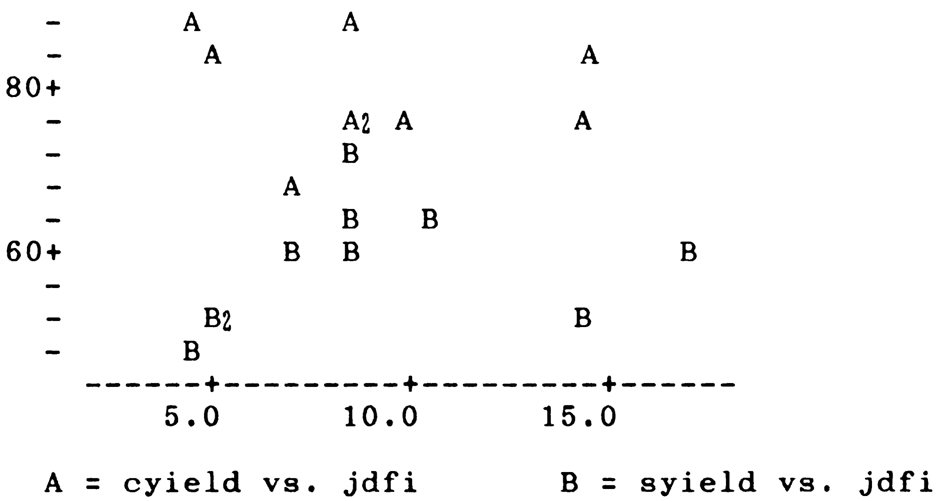
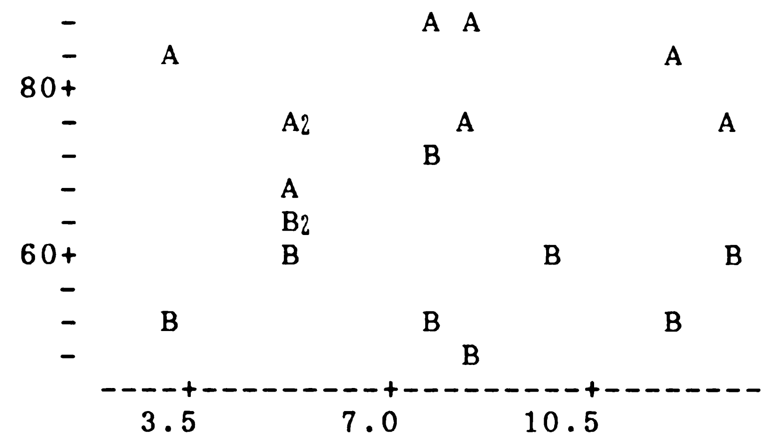
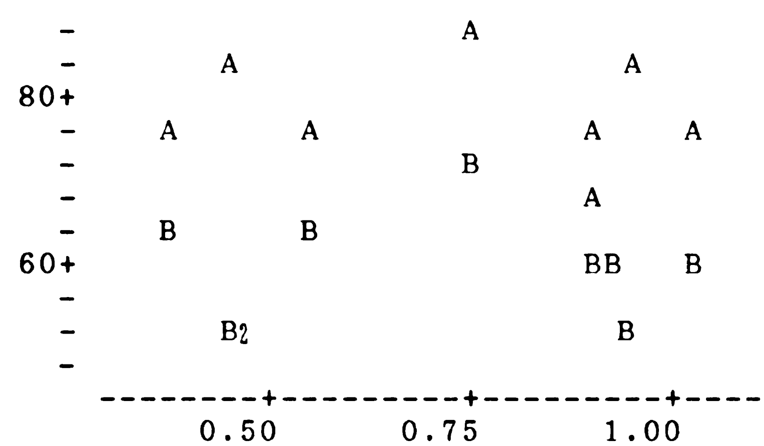


Figure D10. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation dry stress index (jdfi,m*hr/hr) for July, 1986 at the Bannister site.



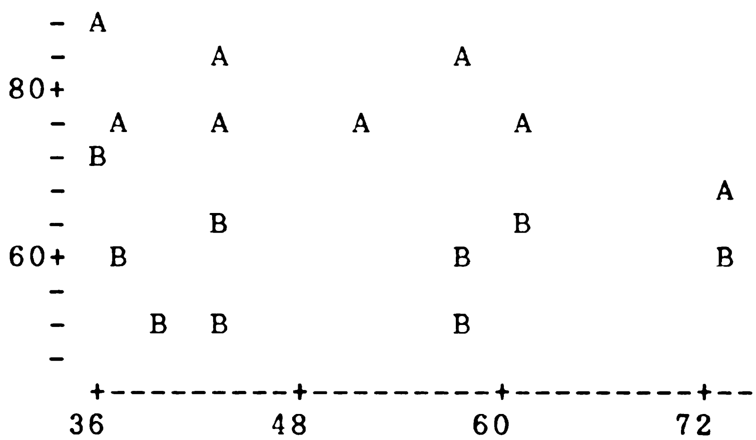
A = cyield vs. jwfi   B = syield vs. jwfi

Figure D11. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation wet stress index (jwfi,m*hr/hr) for July, 1986 at the Bannister site.



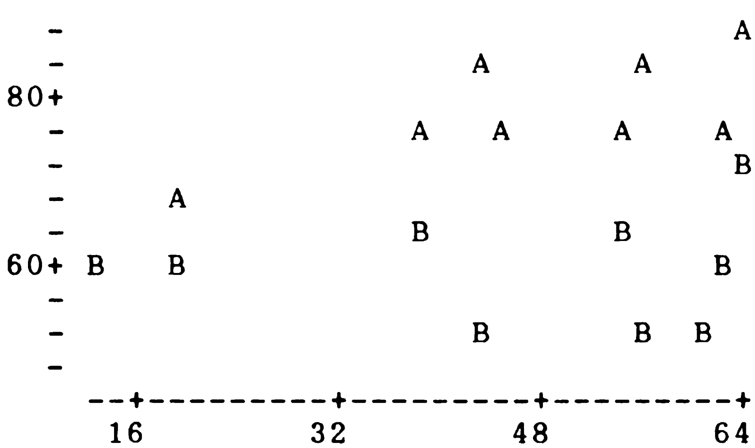
A = cyield vs. awtd   B = syield vs. awtd

Figure D12. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. mean depth to the water table (awtd,m) during August, 1986 at the Bannister site.



A = cyield vs. atimeb   B = syield vs. atimeb

Figure D13. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was below the mean water table depth (atimeb,%) during August, 1986 at the Bannister site.



A = cyield vs. atimea   B = syield vs. atimea

Figure D14. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was above the mean water table depth (atimea,%) during August, 1986 at the Bannister site.

```
  -               A
  -                  A     A
80+
  -       A         A A           A
  -               B
  -           A
  -       B           B
60+     B     B                   B
  -
  -        B         B     B
  -
    +---------+---------+---------+--
  0.0       2.5       5.0       7.5
```

A = cyield vs. adfi B = syield vs. adfi

Figure D15. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation dry stress index (adfi,m*hr/hr) for August, 1986 at the Bannister site.

```
  -                 A
  -            A  A
80+
  -   A      A    A                A
  -                 B
  -   A
  -   B           B
60+ B B                            B
  -
  -        B   B  B
  -
    +---------+---------+---------+--
  0.0       4.0       8.0      12.0
```

A = cyield vs. awfi B = syield vs. awfi

Figure D16. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation wet stress index (awfi,m*hr/hr) for August, 1986 at the Bannister site.

```
  -
  -                              B
  -                 B
  -  A2
84+                 A
  -                 B
  -  A2             A
  -                              A
  -                 B
72+  B
  -
    ------+---------+---------+------
        8.0      12.0      16.0
```

A = cyield vs. spacing   B = syield vs. spacing

Figure D17. Scatter plot of relative corn yield (cyield,%,A) and relatvie soybean yield (syield,%,B) vs. spacing of underground pipe system laterals (spacing,m) during the 1987 growing season at the Bannister site.

```
  -
  -       B
  -   B
  -      A    A
84+                                A
  -                  B
  -      B    B      A
  -       A
  -                                B
72+     B
  -
    --+---------+---------+---------+
     0.90      1.20      1.50      1.80
```

A = cyield vs. swtd   B = syield vs. swtd

Figure D18. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. mean depth to the water table (swtd,m) during the 1987 growing season at the Bannister site.

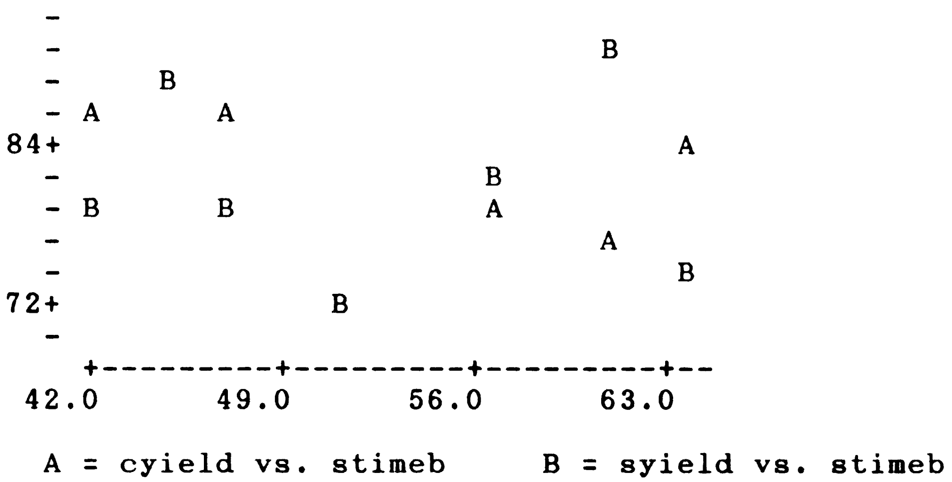


Figure D19. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was below the mean water table depth (stimeb,%) during the 1987 growing season at the Bannister site.

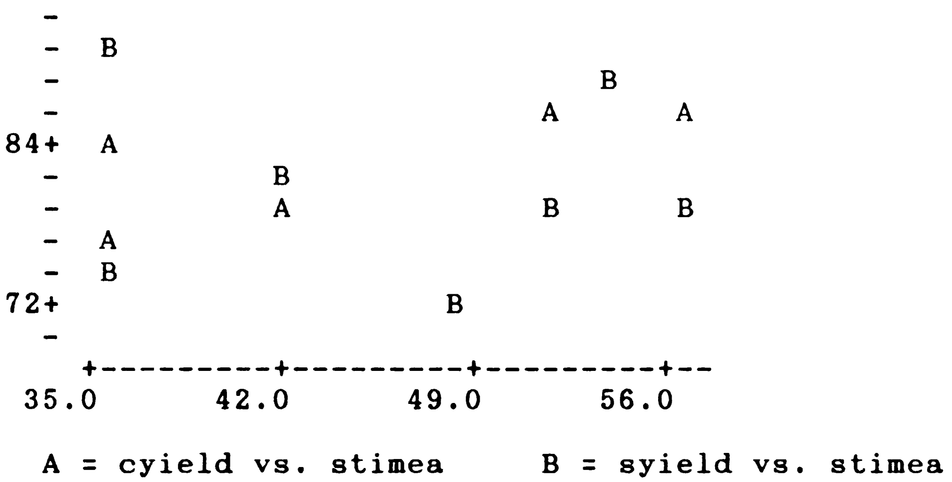


Figure D20. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was above the mean water table depth (stimea,%) during the 1987 growing season at the Bannister site.

```
  -
  -                       B
  -                   B
  -   A                             A
84+             A
  -                             B
  -   B                         A   B
  -                       A
  -             B
72+                             B
  -
    --------+---------+---------+----
         20.0      25.0      30.0
```

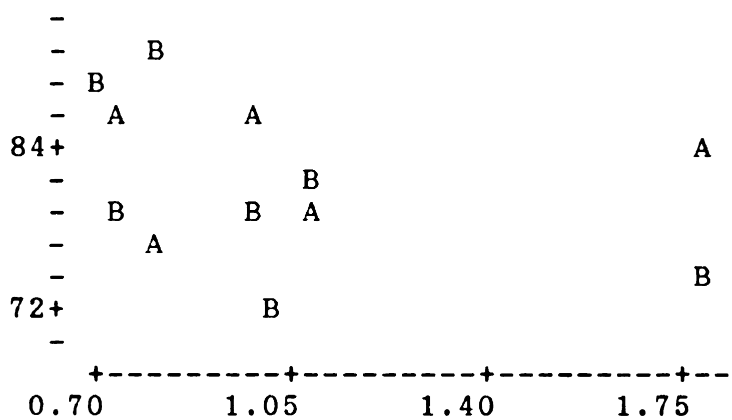
A = cyield vs. sdfi   B = syield vs. sdfi

Figure D21. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation dry stress index (sdfi,m*hr/hr) for the 1987 growing season at the Bannister site.

```
  -
  -         B
  -                           B
  -                   A             A
84+    A
  -                 B
  -                 A B             B
  -         A
  -    B
72+                        B
  -
    --------+---------+---------+----
         16.0      24.0      32.0
```

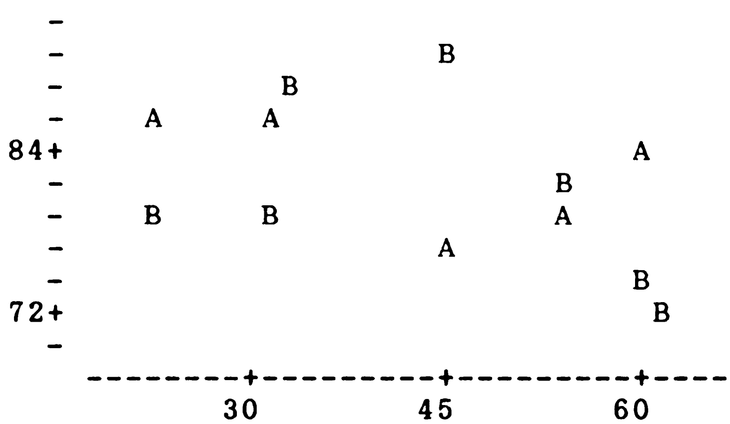
A = cyield vs. swfi   B = syield vs. swfi

Figure D22. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation wety stress index (swfi,m*hr/hr) for the 1987 growing season at the Bannister site.



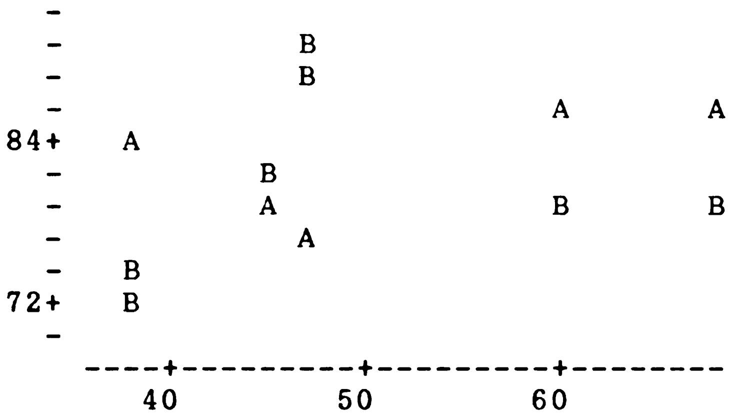
A = cyield vs. jwtd B = syield vs. jwtd

Figure D23. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. mean depth to the water table (jwtd,m) during July, 1987 at the Bannister site.



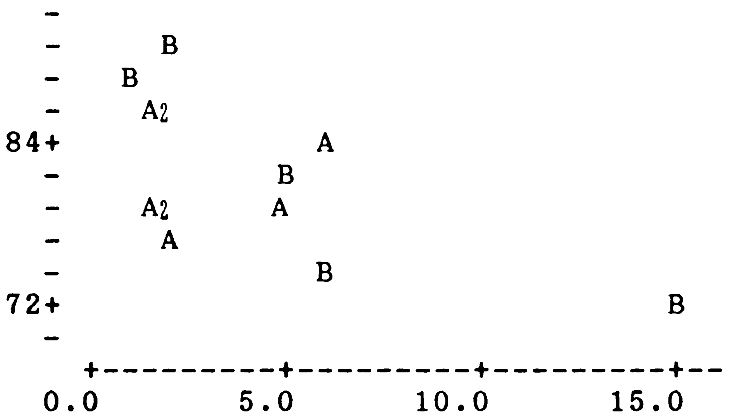
A = cyield vs. jtimeb B = syield vs. jtimeb

Figure D24. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was below the mean water table depth (jtimeb,%) during July, 1987 at the Bannister site.



A = cyield vs. jtimea B = syield vs. jtimea

Figure D25. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was above the mean water table depth (jtimea,%) during July, 1987 at the Bannister site.



A = cyield vs. jdfi B = syield vs. jdfi

Figure D26. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation dry stress index (jdfi,m*hr/hr) for July, 1987 at the Bannister site.

```
  -
  -      B
  -   B
  -       A    A
84+          A
  -             B
  -       B    BA
  -      A
  -          B
72+                                 B
  -
    ------+---------+---------+------
         2.5      5.0       7.5
```

A = cyield vs. jwfi   B = syield vs. jwfi

Figure D27. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation wet stress index (jwfi,m*hr/hr) for July, 1987 at the Bannister site.

```
  -
  -          B
  -     B
  -        A    A
84+                                A
  -                   B
  -        B    B     A
  -          A
  -                                B
72+  B
  -
    --+---------+---------+---------+
   0.90      1.20      1.50      1.80
```

A = cyield vs. awtd   B = syield vs. awtd

Figure D28. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. mean depth to the water table (awtd,m) during August, 1987 at the Bannister site.

```
     -
     -                           B
     -                    B
     -        A          A
   84+                                A
     -                   B
     -        B          A2
     -                           A
     -                                B
   72+ B
     -
       ----+---------+---------+--------
          40        50        60
```

A = cyield vs. atimeb B = syield vs. atimeb

Figure D29. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was below the mean water table depth (atimeb,%) during August, 1987 at the Bannister site.

```
     -
     -     B
     -                B
     -                A         A
   84+      A
     -               B
     -               AB         B
     -     A
     -      B
   72+                               B
     -
       --------+---------+---------+----
              36        48        60
```

A = cyield vs. atimea B = syield vs. atimea

Figure D30. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was above the mean water table depth (atimea,%) during August, 1987 at the Bannister site.

```
  -
  -       B
  -                              B
  -         A                    A
84+                         A
  -           B
  -         B A                  B
  -       A
  -                         B
72+    B
  -

    --+---------+---------+---------+
    3.0       6.0       9.0      12.0
```

A = cyield vs. adfi   B = syield vs. adfi

Figure D31. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation dry stress index (adfi,m*hr/hr) for August, 1987 at the Bannister site.

```
  -
  -   B
  -                               B
  -                    A           A
84+             A
  -            B
  -            A       B           B
  -   A
  -             B
72+                 B
  -

    ----+---------+---------+--------
      2.5       5.0       7.5
```

A = cyield vs. awfi   B = syield vs. awfi

Figure D32. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation wet stress index (awfi,m*hr/hr) for August, 1987 at the Bannister site.

```
90+   A
  -   A                             A
  -   B                             B
  -   A
  -
60+
  -   B
  -
  -
  -   B
30+
    --+---------+---------+---------+
   12.0      16.0      20.0      24.0

  A = cyield vs. spacing    B = syield vs. spacing
```

Figure D33. Scatter plot of relative corn yield (cyield,%,A) and relatvie soybean yield (syield,%,B) vs. spacing of underground pipe system laterals (spacing,m) during the 1987 growing season at the St. Johns site.

```
90+                         A
  -   A                        A
  -   B                         B
  -                             A
  -
60+
  -                            B
  -
  -
  -                         B
30+
    +---------+---------+---------+--
 1.00      1.10      1.20      1.30

  A = cyield vs. swtd       B = syield vs. swtd
```

Figure D34. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. mean depth to the water table (swtd,m) during the 1987 growing season at the St. Johns site.

```
90+            A
  -              A                 A
  -    B                           B
  -    A
  -
60+
  -              B
  -
  -
  -            B
30+
    ------+---------+---------+------
       44.0      48.0      52.0

  A = cyield vs. stimeb     B = syield vs. stimeb
```

Figure D35. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was below the mean water table depth (stimeb,%) during the 1987 growing season at the St. Johns site.

```
90+                               A
  -   A                      A
  -   B                           B
  -                               A
  -
60+
  -                          B
  -
  -
  -                               B
30+
    ------+---------+---------+------
       45.5      49.0      52.5

  A = cyield vs. stimea     B = syield vs. stimea
```

Figure D36. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was above the mean water table depth (stimea,%) during the 1987 growing season at the St. Johns site.

```
90+             A
  - A                               A
  - B     B
  -       A
  -
60+
  -                                 B
  -
  -
  -             B
30+
    --+---------+---------+---------+
     30        60        90       120
```

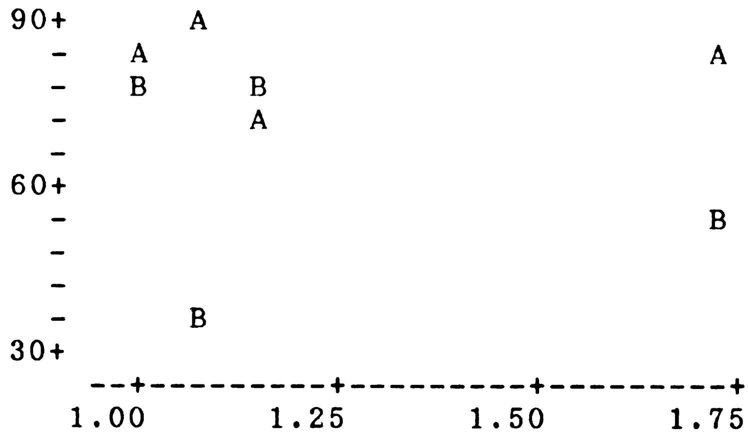
A = cyield vs. sdfi   B = syield vs. sdfi

Figure D37. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation dry stress index (sdfi,m*hr/hr) for the 1987 growing season at the St. Johns site.

```
90+                 A
  -    A                           A
  -    B       B
  -            A
  -
60+
  -                                B
  -
  -
  -                 B
30+
    --------+---------+---------+----
           40        80       120
```

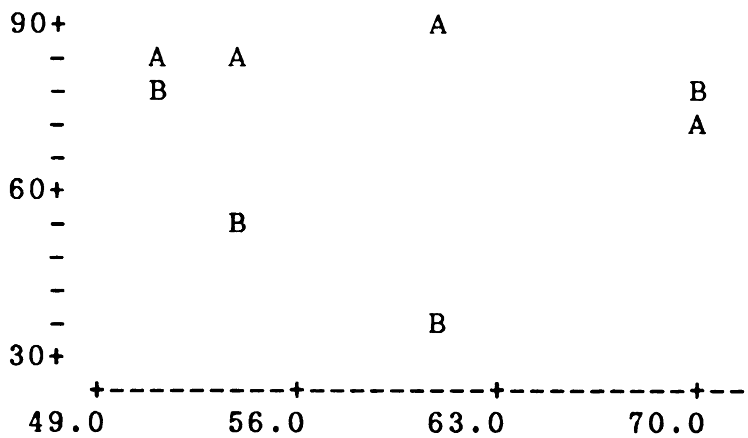
A = cyield vs. swfi   B = syield vs. swfi

Figure D38. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation wety stress index (swfi,m*hr/hr) for the 1987 growing season at the St. Johns site.



A = cyield vs. jwtd B = syield vs. jwtd

Figure D39. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. mean depth to the water table (jwtd,m) during July, 1987 at the St. Johns site.



A = cyield vs. jtimeb B = syield vs. jtimeb

Figure D40. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was below the mean water table depth (jtimeb,%) during July, 1987 at the St. Johns site.

```
90+                 A
  -                           A  A
  -    B                         B
  -    A
  -
60+
  -                           B
  -
  -
  -                 B
30+
    +---------+---------+---------+--
   20        30        40        50
```

A = cyield vs. jtimea   B = syield vs. jtimea

Figure D41. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was above the mean water table depth (jtimea,%) during July, 1987 at the St. Johns site.

```
90+      A
  - A                              A
  - B  B
  -    A
  -
60+
  -                                B
  -
  -
  -      B
30+
    ------+---------+---------+------
         20        40        60
```

A = cyield vs. jdfi   B = syield vs. jdfi

Figure D42. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation dry stress index (jdfi,m*hr/hr) for July, 1987 at the St. Johns site.

```
90+      A
  -     A                         A
  -   B B
  -   A
  -
60+
  -                               B
  -
  -
  -      B
30+
    +---------+---------+---------+--
    0        20        40        60
```

A = cyield vs. jwfi   B = syield vs. jwfi

Figure D43. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation wet stress index (jwfi,m*hr/hr) for July, 1987 at the St. Johns site.

```
90+                              A
  -   AA
  -   B              B
  -                  A
  -
60+
  -    B
  -
  -
  -                              B
30+
    ------+---------+---------+------
       1.05      1.20      1.35
```

A = cyield vs. awtd   B = syield vs. awtd

Figure D44. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. mean depth to the water table (awtd,m) during August, 1987 at the St. Johns site.

```
90+                               A
  -     A     A
  -     B                   B
  -                         A
  -
60+
  -           B
  -
  -
  -                               B
30+
    +---------+---------+---------+--
 40.0      45.0      50.0      55.0
```

A = cyield vs. atimeb   B = syield vs. atimeb

Figure D45. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was below the mean water table depth (atimeb,%) during August, 1987 at the St. Johns site.

```
90+    A
  -                       A       A
  -                   B   B
  -                   A
  -
60+
  -                               B
  -
  -
  -    B
30+
    ------+---------+---------+------
         30        40        50
```

A = cyield vs. atimea   B = syield vs. atimea

Figure D46. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was above the mean water table depth (atimea,%) during August, 1987 at the St. Johns site.

```
90+   A
  -       A                         A
  -       B        B
  -                A
  -
60+
  -                                 B
  -
  -
  -   B
30+
    --------+---------+---------+----
          7.0      14.0      21.0
```

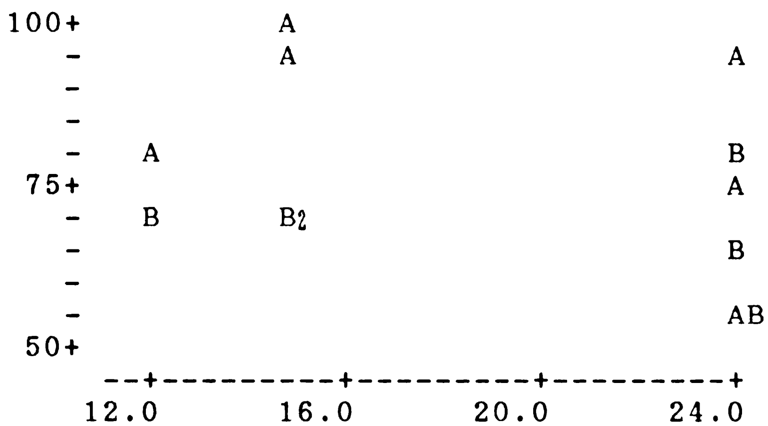
A = cyield vs. adfi   B = syield vs. adfi

Figure D47. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation dry stress index (adfi,m*hr/hr) for August, 1987 at the St. Johns site.

```
90+   A
  -       A                     A
  -       B   B
  -           A
  -
60+
  -                             B
  -
  -
  -   B
30+
    +---------+---------+---------+--
    0        10        20        30
```

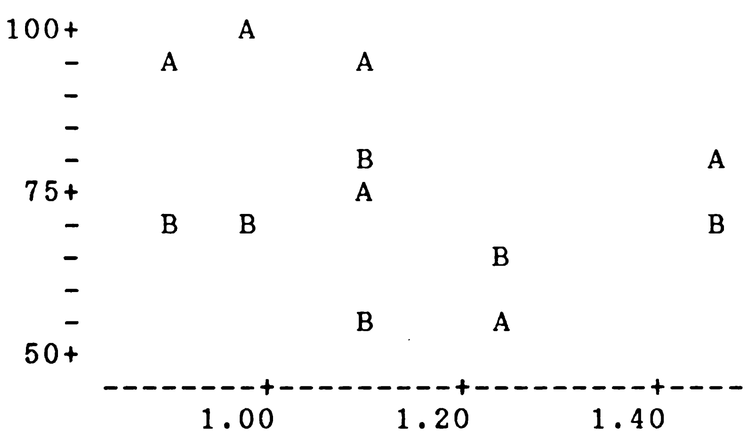
A = cyield vs. awfi   B = syield vs. awfi

Figure D48. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation wet stress index (awfi,m*hr/hr) for August, 1987 at the St. Johns site.



A = cyield vs. spacing   B = syield vs. spacing

Figure D49. Scatter plot of relative corn yield (cyield,%,A) and relatvie soybean yield (syield,%,B) vs. spacing of underground pipe system laterals (spacing,m) during the 1988 growing season at the St. Johns site.



A = cyield vs. swtd   B = syield vs. swtd

Figure D50. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. mean depth to the water table (swtd,m) during the 1988 growing season at the St. Johns site.

```
      100+     A
         -              A       A
         -
         -
         -              B               A
       75+   A
         -     B                B       B
         -                  B
         -
         -   B              A
       50+
           ------+---------+---------+------
                45        60        75

        A = cyield vs. stimeb     B = syield vs. stimeb
```

Figure D51. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was below the mean water table depth (stimeb,%) during the 1988 growing season at the St. Johns site.

```
      100+                             A
         -               AA
         -
         -
         -     A         B
       75+                                A
         -     B          B            B
         -                B
         -
         -                A               B
       50+
           +---------+---------+---------+--
           0        20        40        60

        A = cyield vs. stimea     B = syield vs. stimea
```

Figure D52. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was above the mean water table depth (stimea,%) during the 1988 growing season at the St. Johns site.

```
100+                 A
   -     A                          A
   -
   -
   -     BA
 75+           A
   -      B          B              B
   -    B
   -
   -    A      B
 50+
     +---------+---------+---------+--
     0        60        120       180

      A = cyield vs. sdfi       B = syield vs. sdfi
```

Figure D53. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation dry stress index (sdfi,m*hr/hr) for the 1988 growing season at the St. Johns site.

```
100+                                A
   -    A                  A
   -
   -
   -  A B
 75+                        A
   -  B                    B        B
   -    B
   -
   -    A                   B
 50+
     +---------+---------+---------+--
     0        40        80        120

      A = cyield vs. swfi       B = syield vs. swfi
```

Figure D54. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation wety stress index (swfi,m*hr/hr) for the 1988 growing season at the St. Johns site.

```
100+    A
   -      A       A
   -
   -
   -              B                 A
 75+            A
   -    B B                         B
   -                     B
   -
   -            B        A
 50+
     --------+---------+---------+----
          1.00      1.20      1.40

   A = cyield vs. jwtd      B = syield vs. jwtd
```

Figure D55. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. mean depth to the water table (jwtd,m) during July, 1988 at the St. Johns site.

```
100+        A
   -   A                            A
   -
   -
   -                   A            B
 75+        A
   -   B    B          B
   -             B
   -
   -        B    A
 50+
     --------+---------+---------+----
          35.0      42.0      49.0

   A = cyield vs. jtimeb    B = syield vs. jtimeb
```

Figure D56. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was below the mean water table depth (jtimeb,%) during July, 1988 at the St. Johns site.

```
  100+                            A
     -     A                        A
     -
     -
     -
     -  A  B
   75+                         A
     -  B                           B B
     -             B
     -
     -             A           B
   50+
      ----+---------+---------+--------
         30        45        60
```

A = cyield vs. jtimea   B = syield vs. jtimea

Figure D57. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was above the mean water table depth (jtimea,%) during July, 1988 at the St. Johns site.

```
  100+                              A
     -   A        A
     -
     -
     - A B
   75+       A
     - B          B                 B
     -  B
     -
     -  A    B
   50+
      +---------+---------+---------+--
     0.0      8.0      16.0      24.0
```

A = cyield vs. jdfi   B = syield vs. jdfi

Figure D58. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation dry stress index (jdfi,m*hr/hr) for July, 1988 at the St. Johns site.

```
100+                                   A
   -  A            A
   -
   -
   - AB
 75+       A
   - B             B                   B
   -  B
   -
   -  A    B
 50+
     +---------+---------+---------+--
     0        15        30        45
```

A = cyield vs. jwfi   B = syield vs. jwfi

Figure D59. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation wet stress index (jwfi,m*hr/hr) for July, 1988 at the St. Johns site.

```
100+    A
   -   A          A
   -
   -
   -              B           A
 75+             A
   -   BB                     B
   -                      B
   -
   -             B        A
 50+
     --------+---------+---------+----
           1.00      1.20      1.40
```

A = cyield vs. awtd   B = syield vs. awtd

Figure D60. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. mean depth to the water table (awtd,m) during August, 1988 at the St. Johns site.

```
100+                             A
   -                            A   A
   -
   -
   -   A                            B
 75+       A
   -   B                        BB
   -               B
   -
   -       B       A
 50+
     +---------+---------+---------+--
    20        30        40        50
```

A = cyield vs. atimeb   B = syield vs. atimeb

Figure D61. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was below the mean water table depth (atimeb,%) during August, 1988 at the St. Johns site.

```
100+                A
   -    A A
   -
   -
   -    B     A
 75+                               A
   -      B   B     B
   -            B
   -
   -            A                  B
 50+
     --+---------+---------+---------+
      30        45        60        75
```

A = cyield vs. atimea   B = syield vs. atimea

Figure D62. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. time water table was above the mean water table depth (atimea,%) during August, 1988 at the St. Johns site.

```
100+                            A
   -     A            A
   -
   -
   -  A  B
 75+           A
   -  B               B         B
   -   B
   -
   -   A       B
 50+
     +---------+---------+---------+--
   0.0       5.0      10.0      15.0

   A = cyield vs. adfi       B = syield vs. adfi
```

Figure D63. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation dry stress index (adfi,m*hr/hr) for August, 1988 at the St. Johns site.

```
100+                             A
   -    A         A
   -
   -
   -  A B
 75+                             A
   -  B           B              B
   -    B
   -
   -    A                        B
 50+
     +---------+---------+---------+--
   0.0       5.0      10.0      15.0

   A = cyield vs. awfi       B = syield vs. awfi
```

Figure D64. Scatter plot of relative corn yield (cyield,%,A) and relative soybean yield (syield,%,B) vs. the water table fluctuation wet stress index (awfi,m*hr/hr) for August, 1988 at the St. Johns site.

APPENDIX E

FIELD DATA STATISTICAL SUMMARIES

Table E1a. Field data used for linear regression analyses from the 1986 Bannister site growing season.

ROW	zone	cyield	syield	spacing	swtd	stimeb	sdistb	stimea	sdista
1	1	75	60	12	0.81	31	0.407	67	0.189
2	2	86	48	6	0.48	29	0.154	68	0.066
3	2	*	52	12	0.47	33	0.135	65	0.069
4	2	83	51	18	0.45	49	0.084	43	0.095
5	3	75	63	6	0.58	58	0.143	41	0.202
6	3	83	52	18	0.77	54	0.135	44	0.168
7	4	75	63	6	0.61	68	0.071	30	0.158
8	4	68	58	18	0.72	41	0.163	58	0.115
9	5	77	*	6	0.79	63	0.094	35	0.166
10	7	*	58	6	0.77	62	0.119	37	0.200
11	8	88	71	12	0.81	52	0.083	43	0.099

ROW	jwtd	jtimeb	jdistb	jtimea	jdista	awtd	atimeb	adistb	atimea
1	0.66	38	0.106	57	0.070	1.02	37	0.394	62
2	0.45	33	0.074	64	0.038	*	*	*	*
3	0.45	35	0.073	57	0.045	0.44	39	0.168	61
4	0.45	54	0.033	34	0.052	0.45	43	0.169	56
5	0.69	61	0.050	30	0.102	0.37	43	0.105	55
6	0.72	54	0.094	44	0.114	0.95	57	0.063	43
7	0.65	60	0.041	38	0.066	0.54	61	0.049	38
8	0.66	53	0.048	39	0.066	0.91	73	0.017	19
9	0.83	63	0.067	33	0.126	0.90	52	0.071	45
10	0.75	62	0.082	35	0.146	0.93	58	0.011	13
11	0.84	52	0.061	46	0.068	0.75	36	0.129	64

ROW	adista	sdfi	swfi	jdfi	jwfi	adfi	awfi
1	0.237	37	81	8.4	12.7	7.5	12.5
2	*	9	20	4.3	8.3	*	*
3	0.106	11	21	4.8	7.8	1.7	2.7
4	0.131	19	16	5.1	3.3	4.3	5.6
5	0.084	55	39	10.6	5.2	4.6	5.7
6	0.084	42	34	14.5	11.9	5.8	4.4
7	0.079	31	14	8.3	5.3	1.4	0.8
8	0.063	27	38	7.2	5.3	2.4	0.6
9	0.082	45	25	14.8	7.9	4.1	3.6
10	0.050	52	31	17.0	9.6	1.0	0.2
11	0.072	19	16	8.6	7.7	3.5	6.3

Table E1b. Statistical summary of the field data used for regression analyses from the 1986 Bannister site growing season.

	N	N*	MEAN	MEDIAN	TRMEAN	STDEV	SEMEAN
cyield	9	2	78.89	77.00	78.89	6.47	2.16
syield	10	1	57.60	58.00	57.13	7.01	2.22
spacing	11	0	10.91	12.00	10.67	5.24	1.58
swtd	11	0	0.6600	0.7200	0.6667	0.1453	0.0438
stimeb	11	0	49.09	52.00	49.22	13.73	4.14
sdistb	11	0	0.1444	0.1350	0.1233	0.0925	0.0279
stimea	11	0	48.27	43.00	48.11	13.70	4.13
sdista	11	0	0.1388	0.1580	0.1399	0.0514	0.0155
jwtd	11	0	0.6500	0.6600	0.6511	0.1432	0.0432
jtimeb	11	0	51.36	54.00	52.11	11.03	3.33
jdistb	11	0	0.06627	0.06700	0.06556	0.02252	0.00679
jtimea	11	0	43.36	39.00	42.56	11.39	3.43
jdista	11	0	0.0812	0.0680	0.0788	0.0354	0.0107
awtd	10	1	0.7260	0.8250	0.7338	0.2499	0.0790
atimeb	10	1	49.90	47.50	48.75	12.25	3.87
adistb	10	1	0.1176	0.0880	0.0964	0.1122	0.0355
atimea	10	1	45.60	50.00	47.37	17.88	5.65
adista	10	1	0.0988	0.0830	0.0876	0.0534	0.0169
sdfi	11	0	31.55	31.00	31.44	15.98	4.82
swfi	11	0	30.45	25.00	26.67	19.01	5.73
jdfi	11	0	9.42	8.40	9.14	4.33	1.31
jwfi	11	0	7.727	7.800	7.667	2.895	0.873
adfi	10	1	3.630	3.800	3.475	2.067	0.654
awfi	10	1	4.24	4.00	3.71	3.66	1.16

	MIN	MAX	Q1	Q3
cyield	68.00	88.00	75.00	84.50
syield	48.00	71.00	51.75	63.00
spacing	6.00	18.00	6.00	18.00
swtd	0.4500	0.8100	0.4800	0.7900
stimeb	29.00	68.00	33.00	62.00
sdistb	0.0710	0.4070	0.0840	0.1540
stimea	30.00	68.00	37.00	65.00
sdista	0.0660	0.2020	0.0950	0.1890
jwtd	0.4500	0.8400	0.4500	0.7500
jtimeb	33.00	63.00	38.00	61.00
jdistb	0.03300	0.10600	0.04800	0.08200
jtimea	30.00	64.00	34.00	57.00
jdista	0.0380	0.1460	0.0520	0.1140
awtd	0.3700	1.0200	0.4475	0.9350
atimeb	36.00	73.00	38.50	58.75
adistb	0.0110	0.3940	0.0410	0.1682
atimea	13.00	64.00	33.25	61.25
adista	0.0500	0.2370	0.0697	0.1123
sdfi	9.00	55.00	19.00	45.00
swfi	14.00	81.00	16.00	38.00
jdfi	4.30	17.00	5.10	14.50
jwfi	3.300	12.700	5.300	9.600
adfi	1.000	7.500	1.625	4.900
awfi	0.20	12.50	0.75	5.85

Table E2a. Field data used for linear regression analyses from the 1987 Bannister site growing season.

ROW	zone	cyield	syield	spacing	swtd	stimeb	sdistb	stimea	sdista
1	3	86	79	6	1.15	42	0.187	57	0.138
2	4	86	80	6	0.99	47	0.261	52	0.237
3	4	78	92	18	1.03	61	0.124	36	0.210
4	5	*	71	6	0.97	51	0.186	48	0.198
5	5	*	89	12	0.89	45	0.220	54	0.184
6	6	83	74	12	1.76	64	0.101	36	0.182
7	8	80	82	12	1.30	57	0.146	42	0.196

ROW	jwtd	jtimeb	jdistb	jtimea	jdista	awtd	atimeb	adistb	atimea
1	0.98	31	0.073	60	0.038	1.19	43	0.134	56
2	0.73	23	0.129	68	0.044	1.04	54	0.180	45
3	0.82	45	0.055	47	0.052	1.12	62	0.051	31
4	1.01	62	0.120	38	0.198	0.87	36	0.143	63
5	0.71	33	0.052	47	0.037	0.95	55	0.174	44
6	1.77	60	0.081	38	0.129	1.78	67	0.099	32
7	1.09	54	0.079	45	0.093	1.39	54	0.083	43

ROW	adista	sdfi	swfi	jdfi	jwfi	adfi	awfi
1	0.102	17	24	1.3	2.6	4.8	6.3
2	0.216	32	35	1.3	3.8	11.0	9.2
3	0.102	27	16	2.2	2.3	4.1	2.0
4	0.081	30	28	14.8	9.0	3.2	5.6
5	0.217	25	30	1.2	1.6	11.1	8.9
6	0.205	22	12	5.8	3.6	9.6	4.6
7	0.105	30	22	4.8	4.0	5.4	4.3

Table E2b. Statistical summary of the field data used for regression analyses from the 1987 Bannister site growing season.

	N	N*	MEAN	MEDIAN	TRMEAN	STDEV	SEMEAN
cyield	5	2	82.60	83.00	82.60	3.58	1.60
syield	7	0	81.00	80.00	81.00	7.53	2.85
spacing	7	0	10.29	12.00	10.29	4.54	1.71
swtd	7	0	1.156	1.030	1.156	0.298	0.113
stimeb	7	0	52.43	51.00	52.43	8.40	3.18
sdistb	7	0	0.1750	0.1860	0.1750	0.0557	0.0210
stimea	7	0	46.43	48.00	46.43	8.56	3.24
sdista	7	0	0.1921	0.1960	0.1921	0.0302	0.0114
jwtd	7	0	1.016	0.980	1.016	0.363	0.137
jtimeb	7	0	44.00	45.00	44.00	15.34	5.80
jdistb	7	0	0.0841	0.0790	0.0841	0.0298	0.0113
jtimea	7	0	49.00	47.00	49.00	11.17	4.22
jdista	7	0	0.0844	0.0520	0.0844	0.0606	0.0229
awtd	7	0	1.191	1.120	1.191	0.310	0.117
atimeb	7	0	53.00	54.00	53.00	10.58	4.00
adistb	7	0	0.1234	0.1340	0.1234	0.0478	0.0181
atimea	7	0	44.86	44.00	44.86	11.65	4.40
adista	7	0	0.1469	0.1050	0.1469	0.0622	0.0235
sdfi	7	0	26.14	27.00	26.14	5.27	1.99
swfi	7	0	23.86	24.00	23.86	8.01	3.03
jdfi	7	0	4.49	2.20	4.49	4.91	1.86
jwfi	7	0	3.843	3.600	3.843	2.437	0.921
adfi	7	0	7.03	5.40	7.03	3.41	1.29
awfi	7	0	5.843	5.600	5.843	2.568	0.971

	MIN	MAX	Q1	Q3
cyield	78.00	86.00	79.00	86.00
syield	71.00	92.00	74.00	89.00
spacing	6.00	18.00	6.00	12.00
swtd	0.890	1.760	0.970	1.300
stimeb	42.00	64.00	45.00	61.00
sdistb	0.1010	0.2610	0.1240	0.2200
stimea	36.00	57.00	36.00	54.00
sdista	0.1380	0.2370	0.1820	0.2100
jwtd	0.710	1.770	0.730	1.090
jtimeb	23.00	62.00	31.00	60.00
jdistb	0.0520	0.1290	0.0550	0.1200
jtimea	38.00	68.00	38.00	60.00
jdista	0.0370	0.1980	0.0380	0.1290
awtd	0.870	1.780	0.950	1.390
atimeb	36.00	67.00	43.00	62.00
adistb	0.0510	0.1800	0.0830	0.1740
atimea	31.00	63.00	32.00	56.00
adista	0.0810	0.2170	0.1020	0.2160
sdfi	17.00	32.00	22.00	30.00
swfi	12.00	35.00	16.00	30.00
jdfi	1.20	14.80	1.30	5.80
jwfi	1.600	9.000	2.300	4.000
adfi	3.20	11.10	4.10	11.00
awfi	2.000	9.200	4.300	8.900

Table E3a. Field data used for linear regression analyses from the 1987 St. Johns site growing season.

ROW	zone	cyield	syield	spacing	swtd	stimeb	sdistb	stimea	sdista
1	2	83	54	12	1.29	47	0.390	52	0.351
2	3	87	35	12	1.26	46	0.222	54	0.189
3	3	71	77	12	1.30	43	0.186	54	0.148
4	4	84	80	24	1.02	54	0.063	44	0.077

ROW	jwtd	jtimeb	jdistb	jtimea	jdista	awtd	atimeb	adistb	atimea
1	1.72	54	0.690	46	0.796	1.00	45	0.185	54
2	1.07	61	0.083	36	0.139	1.39	55	0.025	27
3	1.15	70	0.128	23	0.383	1.21	52	0.072	42
4	0.99	51	0.123	49	0.127	0.99	42	0.051	46

ROW	adista	sdfi	swfi	jdfi	jwfi	adfi	awfi
1	0.155	119	132	69.1	59.9	23.6	28.2
2	0.051	61	72	18.0	10.7	3.1	1.5
3	0.090	42	53	13.9	4.7	12.1	9.7
4	0.047	24	19	8.8	8.6	5.3	5.8

Table E3b. Statistical summary of the field data used for regression analyses from the 1987 St. Johns site growing season.

	N	MEAN	MEDIAN	TRMEAN	STDEV	SEMEAN
cyield	4	81.25	83.50	81.25	7.04	3.52
syield	4	61.5	65.5	61.5	21.1	10.6
spacing	4	15.00	12.00	15.00	6.00	3.00
swtd	4	1.2175	1.2750	1.2175	0.1328	0.0664
stimeb	4	47.50	46.50	47.50	4.65	2.33
sdistb	4	0.2153	0.2040	0.2153	0.1349	0.0675
stimea	4	51.00	53.00	51.00	4.76	2.38
sdista	4	0.1912	0.1685	0.1912	0.1161	0.0581
jwtd	4	1.233	1.110	1.233	0.331	0.166
jtimeb	4	59.00	57.50	59.00	8.45	4.22
jdistb	4	0.256	0.126	0.256	0.290	0.145
jtimea	4	38.50	41.00	38.50	11.73	5.87
jdista	4	0.361	0.261	0.361	0.313	0.156
awtd	4	1.1475	1.1050	1.1475	0.1909	0.0954
atimeb	4	48.50	48.50	48.50	6.03	3.01
adistb	4	0.0833	0.0615	0.0833	0.0705	0.0353
atimea	4	42.25	44.00	42.25	11.32	5.66
adista	4	0.0857	0.0705	0.0857	0.0501	0.0250
sdfi	4	61.5	51.5	61.5	41.2	20.6
swfi	4	69.0	62.5	69.0	47.4	23.7
jdfi	4	27.4	15.9	27.4	28.0	14.0
jwfi	4	21.0	9.6	21.0	26.1	13.0
adfi	4	11.03	8.70	11.03	9.22	4.61
awfi	4	11.30	7.75	11.30	11.75	5.88

	MIN	MAX	Q1	Q3
cyield	71.00	87.00	74.00	86.25
syield	35.0	80.0	39.8	79.2
spacing	12.00	24.00	12.00	21.00
swtd	1.0200	1.3000	1.0800	1.2975
stimeb	43.00	54.00	43.75	52.25
sdistb	0.0630	0.3900	0.0937	0.3480
stimea	44.00	54.00	46.00	54.00
sdista	0.0770	0.3510	0.0948	0.3105
jwtd	0.990	1.720	1.010	1.577
jtimeb	51.00	70.00	51.75	67.75
jdistb	0.083	0.690	0.093	0.549
jtimea	23.00	49.00	26.25	48.25
jdista	0.127	0.796	0.130	0.693
awtd	0.9900	1.3900	0.9925	1.3450
atimeb	42.00	55.00	42.75	54.25
adistb	0.0250	0.1850	0.0315	0.1567
atimea	27.00	54.00	30.75	52.00
adista	0.0470	0.1550	0.0480	0.1388
sdfi	24.0	119.0	28.5	104.5
swfi	19.0	132.0	27.5	117.0
jdfi	8.8	69.1	10.1	56.3
jwfi	4.7	59.9	5.7	47.6
adfi	3.10	23.60	3.65	20.73
awfi	1.50	28.20	2.58	23.58

Table E4a. Field data used for linear regression analyses from the 1988 St. Johns site growing season.

ROW	zone	cyield	syield	spacing	swtd	stimeb	sdistb	stimea	sdista
1	1	97	71	15	0.90	68	0.208	32	0.439
2	1	77	54	24	1.10	39	0.199	61	0.127
3	2	99	68	15	0.98	42	0.267	56	0.200
4	3	82	71	12	1.45	79	0.021	7	0.224
5	3	57	65	24	1.23	62	0.026	31	0.052
6	4	93	80	24	1.09	55	0.035	29	0.067

ROW	jwtd	jtimeb	jdistb	jtimea	jdista	awtd	atimeb	adistb	atimea
1	0.94	31	0.232	69	0.106	0.89	47	0.086	35
2	1.05	34	0.104	61	0.059	1.08	26	0.171	72
3	0.89	34	0.486	66	0.253	0.92	48	0.141	49
4	1.46	42	0.011	27	0.016	1.47	22	0.019	41
5	1.24	38	0.023	43	0.021	1.24	34	0.023	44
6	1.09	51	0.018	31	0.029	1.09	51	0.018	31

ROW	adista	sdfi	swfi	jdfi	jwfi	adfi	awfi
1	0.117	188	89	9.6	21.0	8.6	6.4
2	0.061	59	93	5.3	9.4	5.0	14.1
3	0.138	94	125	24.2	46.5	13.7	14.1
4	0.010	27	3	0.8	0.5	0.4	0.7
5	0.018	20	10	1.4	1.6	1.2	1.6
6	0.029	22	12	2.1	1.3	2.1	1.3

Table E4b. Statistical summary of the field data used for regression analyses from the 1988 St. Johns site growing season.

	N	MEAN	MEDIAN	TRMEAN	STDEV	SEMEAN
cyield	6	84.17	87.50	84.17	15.85	6.47
syield	6	68.17	69.50	68.17	8.57	3.50
spacing	6	19.00	19.50	19.00	5.59	2.28
swtd	6	1.1250	1.0950	1.1250	0.1950	0.0796
stimeb	6	57.50	58.50	57.50	15.37	6.28
sdistb	6	0.1260	0.1170	0.1260	0.1107	0.0452
stimea	6	36.00	31.50	36.00	19.78	8.07
sdista	6	0.1848	0.1635	0.1848	0.1423	0.0581
jwtd	6	1.1117	1.0700	1.1117	0.2101	0.0858
jtimeb	6	38.33	36.00	38.33	7.28	2.97
jdistb	6	0.1457	0.0635	0.1457	0.1868	0.0763
jtimea	6	49.50	52.00	49.50	18.31	7.47
jdista	6	0.0807	0.0440	0.0807	0.0908	0.0371
awtd	6	1.1150	1.0850	1.1150	0.2155	0.0880
atimeb	6	38.00	40.50	38.00	12.38	5.05
adistb	6	0.0763	0.0545	0.0763	0.0675	0.0276
atimea	6	45.33	42.50	45.33	14.54	5.94
adista	6	0.0622	0.0450	0.0622	0.0539	0.0220
sdfi	6	68.3	43.0	68.3	65.2	26.6
swfi	6	55.3	50.5	55.3	53.1	21.7
jdfi	6	7.23	3.70	7.23	8.93	3.65
jwfi	6	13.38	5.50	13.38	18.01	7.35
adfi	6	5.17	3.55	5.17	5.15	2.10
awfi	6	6.37	4.00	6.37	6.33	2.58

	MIN	MAX	Q1	Q3
cyield	57.00	99.00	72.00	97.50
syield	54.00	80.00	62.25	73.25
spacing	12.00	24.00	14.25	24.00
swtd	0.9000	1.4500	0.9600	1.2850
stimeb	39.00	79.00	41.25	70.75
sdistb	0.0210	0.2670	0.0247	0.2228
stimea	7.00	61.00	23.50	57.25
sdista	0.0520	0.4390	0.0633	0.2778
jwtd	0.8900	1.4600	0.9275	1.2950
jtimeb	31.00	51.00	33.25	44.25
jdistb	0.0110	0.4860	0.0162	0.2955
jtimea	27.00	69.00	30.00	66.75
jdista	0.0160	0.2530	0.0197	0.1427
awtd	0.8900	1.4700	0.9125	1.2975
atimeb	22.00	51.00	25.00	48.75
adistb	0.0180	0.1710	0.0187	0.1485
atimea	31.00	72.00	34.00	54.75
adista	0.0100	0.1380	0.0160	0.1222
sdfi	20.0	188.0	21.5	117.5
swfi	3.0	125.0	8.3	101.0
jdfi	0.80	24.20	1.25	13.25
jwfi	0.50	46.50	1.10	27.38
adfi	0.40	13.70	1.00	9.87
awfi	0.70	14.10	1.15	14.10

APPENDIX F

SILSPACE PROGRAM SOURCE CODE

```
REM ********************************************************************
REM       PROGRAM NAME             SILSPACE.BAS
REM       PROGRAM VERSION          Version 1.01
REM       PROGRAM AUTHOR           H. W. Belcher, MSU
REM       DATE OF LAST REVISION    09/30/89
REM       PROGRAM LANGUAGE  Turbo Basic - Version 1.0
REM--------------------------------------------------------------------
REM This program is used to design the spacing laterals should be
REM installed for subirrigation.
REM--------------------------------------------------------------------
DIM hydc(15),dporosity(15),th(15),length(100)
$INCLUDE "SIINPUT.INC"
$INCLUDE "SILSPACE.INC"
$INCLUDE "SITIME.INC"
$INCLUDE "SIOUTPUT.INC"
$INCLUDE "SISUBR.INC"
END
REM====================================================================
REM   SUBROUTINE NAME            SIINPUT.INC
REM   SUBROUTINE AUTHOR          H. Belcher, MSU
REM   DATE OF LAST REVISION      10/11/89
REM   PROGRAM LANGUAGE           Turbo Basic - Version 1.0
REM--------------------------------------------------------------------
debugoutput1$="off"
debugoutput2$="off"
CLS
PRINTAB(10);"************************************************************"

PRINT
PRINT TAB(10);"SILSPACE - A lateral spacing design program for subirrigation"

PRINT
PRINTAB(10);"************************************************************"

PRINT
PRINT
PRINT
PRINT TAB(28);"      H. W. Belcher      "
PRINT TAB(28);"MICHIGAN STATE UNIVERSITY"
PRINT TAB(28);"      Version: 1.01      "
PRINT TAB(28);"         09/29/89         "
LOCATE 24,26
PRINT "PRESS ANY KEY TO CONTINUE? ";
WHILE LEN(anykey$)=0
   anykey$=INKEY$
WEND

begin:
REM---------------------input data----------------------------
CLS
anykey$=""
PRINT "WILL INPUT DATA COME FROM DISKFILE (f) OR KEYBOARD (k)? "
```

```
WHILE LEN(anykey$)=0:anykey$=INKEY$:WEND
IF anykey$="F" OR anykey$="f" THEN
   INPUT "Enter input file name ............... ";FileName$
   CLS
   OPEN FileName$ FOR INPUT AS #1
   INPUT #1, barrierdepth,nlayers%
   FOR i%=1 TO nlayers%
      INPUT #1, th(i%),hydc(i%),sat(i%),dul(i%)
      n(i%)=sat(i%)-dul(i%)
   NEXT i%
                                I   N   P   U   T         #   1   ,
TileDepth,TileDiameter,TileGrade,TileLength,siWTdepthMidpoint,_
             siWTdepthLateral,sdWTdepthMidpoint,sdWTdepthLateral
   INPUT #1, sirate,drrate,rainfall,rcn,WeirDepth
   CLOSE #1
   REM------------------------debug1 output--------------------------------
   IF debugoutput1$="on" THEN
      LPRINT "barrierdepth = ";barrierdepth
      LPRINT "nlayers% = ";nlayers%
      FOR i%=1 TO nlayers%
         LPRINT "th = ";th(i%),"hydc = ";hydc(i%),"sat = ";sat(i%),_
                "dul = ";dul(i%)
      NEXT i%
      LPRINT "TileDepth = ";TileDepth
      LPRINT "TileDiameter = ";TileDiameter
      LPRINT "TileGrade = ";TileGrade
      LPRINT "TileLength = ";TileLength
      LPRINT "siWTdepthMidpoint = ";siWTdepthMidpoint
      LPRINT "siWTdepthLateral = ";siWTdepthLateral
      LPRINT "sdWTdepthMidpoint = ";sdWTdepthMidpoint
      LPRINT "sdWTdepthLateral = ";sdWTdepthLateral
      LPRINT "sirate = ";sirate
      LPRINT "drrate = ";drrate
      LPRINT "rainfall = ";rainfall
      LPRINT "rcn = ";rcn
      LPRINT "WeirDepth = ";WeirDepth
   END IF
   REM---------------------------------------------------------------------
ELSE
   PRINT "SYSTEM PARAMETERS:"
   PRINT
   INPUT "Enter depth to the lateral pipe (ft)............ ";TileDepth
   INPUT "Enter diameter of the lateral pipe (in)......... ";TileDiameter

   INPUT "Enter minimum grade of the lateral pipe (%)..... ";TileGrade
   INPUT "Enter length of the lateral pipe (ft)........... ";TileLength
   PRINT " For Subirrigation:
   INPUT "     Enter   depth   to   water   table   at   lateral   (ft).....
";siWTdepthLateral
   INPUT "     Enter   depth   to   water   table   at   midpoint   (ft)....
";siWTdepthMidpoint
   PRINT " For Subsurface Drainage:
```

```
   INPUT "    Enter depth to water table at lateral (ft).....
";sdWTdepthLateral
   INPUT "    Enter depth to water table at midpoint (ft)....
";sdWTdepthMidpoint
   INPUT "Enter design subirrigation rate (in/day)......... ";sirate
   INPUT "Enter design subsurface drainage rate (in/day)... ";drrate
   INPUT "Enter design storm rainfall (in)................. ";rainfall
   INPUT "Enter SCS runoff curve number.................... ";rcn
   INPUT "Enter depth to weir following rainfall (ft)...... ";WeirDepth
   PRINT
   PRINT
   PRINT "SOIL PARAMETERS:"
   PRINT
   INPUT "Enter Depth to Barrier (ft)......... ";BarrierDepth
   INPUT "Enter number of soil layers......... ";nlayers
        nlayers%=fix(nlayers)
        totalth=0
   PRINT "  For Surface Layer  Enter layer thickness (in)...... ";
   INPUT "",th(1)
        totalth=totalth+th(1)
   PRINT "                     Enter sat. hydr. cond. (in/hr).. ";
   INPUT "",hydc(1)
   PRINT "                     Enter sat. water content........ ";
   INPUT "",sat(1)
   PRINT "                     Enter dul water content......... ";
   INPUT "",dul(1):n(1)=sat(1)-dul(1)
   IF nlayers%>1 THEN
     FOR i% = 2 TO nlayers%-1
        PRINT "  For Layer ";i%;"     Enter layer thickness (in)..... ";
        INPUT "",th(i%)
             totalth=totalth+th(i%)
        PRINT "                     Enter sat. hydr. cond. (in/hr).. ";
        INPUT "",hydc(i%)
        PRINT "                     Enter sat. water content........ ";
        INPUT "",sat(i%)
        PRINT "                     Enter dul water content......... ";
        INPUT "",dul(i%):n(i%)=sat(i%)-dul(i%)
     NEXT i%
   END IF
   i%=nlayers
   IF barrierdepth*12 > totalth THEN
     th(i%)=barrierdepth*12-totalth
     PRINT "  For Layer ";i%;"     Layer thickness (in) is.........";
     PRINT th(i%)
     PRINT "                     Enter sat. hydr. cond. (in/hr).. ";
     INPUT "",hydc(i%)
     PRINT "                     Enter sat. water content........ ";
     INPUT "",sat(i%)
     PRINT "                     Enter dul water content......... ";
     INPUT "",dul(i%):n(i%)=sat(i%)-dul(i%)
   END IF
END IF
```

```
REM----------------calculate model parameters---------------------
REM Weight k and dporosity for soil layers to 2 feet below tile
FOR i% = 1 TO nlayers%
   dz(i%) = th(i%)
   k=k+hydc(i%)*th(i%)
   dporosity=dporosity+n(i%)*th(i%)
   tdepth=tdepth+th(i%)
   IF tdepth/12>TileDepth+2 THEN EXIT FOR
NEXT i%
k=k/tdepth
dporosity=dporosity/tdepth
REM-----------------calculate rainfall infiltration---------------
s=1000/rcn-10
IF rainfall>.2*s THEN
   runoff=(rainfall-0.2*s)^2/(rainfall+.8*s)
ELSE
   runoff=0
END IF
infiltration=rainfall-runoff
REM------------------------debug2 output-------------------------
IF debugoutput2$="on" THEN
   LPRINT nlayersabove%,nlayersbelow%
   LPRINT "layer","dz","thickness","hydc","n"
   FOR i% = 1 TO nlayers%
      LPRINT i%,dz(i%),th(i%),;
      LPRINT USING "##.##";hydc(i%);
      LPRINT TAB(56);:LPRINT USING "#.##";n(i%)
   NEXT i%
   LPRINT TAB(0);:LPRINT USING "##.##";k;
   LPRINT TAB(10);:LPRINT USING "#.##";dporosity
   LPRINT CHR$(12)
END IF
REM=============================================================
REM      SUBROUTINE NAME         SILSPACE.INC
REM      PROGRAM AUTHORS         P. Gerrish and H. Belcher
REM      DATE OF LAST REVISION   10/09/89
REM      PROGRAM LANGUAGE  Turbo Basic - Version 1.0
REM--------------------------------------------------------------
units$="FPS"
dia=TileDiameter
IF TileDiameter=3 THEN remm=3.5
IF TileDiameter=4 THEN remm=5.1
IF TileDiameter=5 THEN remm=10.0
msd=ABS(sdWTdepthMidpoint-sdWTdepthLateral)
msi=ABS(siWTdepthLateral-siWTdepthMidpoint)
dwtsd=sdWTdepthMidpoint
dwtsi=siWTdepthLateral
CLS
FOR ii%=1 TO 2
   IF ii%=1 THEN
      dq  = drrate
      m   = msd
```

```
      dwt = dwtsd
   END IF
   IF ii%=2  THEN
      dq  = sirate
      m   = msi
      dwt = dwtsi
   END IF
   FOR l = 100 TO 1 STEP -5
      GOSUB CONVERT
      GOSUB QCALC
      IF units$ = "FPS" THEN
         IF (dq-q) < .1 THEN
       GOSUB FINE
       GOSUB sr100
            EXIT FOR
         END IF
      ELSEIF units$ = "CGS" THEN
    dr = dq
    IF (dr-r) < 1 THEN
       GOSUB MFINE
       GOSUB sr100
            EXIT FOR
    END IF
      END IF
   NEXT l
NEXT ii%
REM find minimum spacing
IF ldr < lsi THEN
   FinalLSpacing=ldr
ELSE
   FinalLSpacing=lsi
END IF
PRINT "LATERAL SPACING USED FOR SUBSEQENT CALCULATIONS = ";
PRINT USING "###";CINT(FinalLSpacing);:PRINT " ft."
LOCATE 24,26:anykey$=""
PRINT "PRESS ANY KEY TO CONTINUE? ";
WHILE LEN(anykey$)=0:anykey$=INKEY$:WEND
REM=====================================================================
REM      SUBROUTINE NAME          SITIME.INC
REM      SUBROUTINE AUTHOR H. W. Belcher
REM      DATE OF LAST REVISION    10/13/89
REM      PROGRAMMING LANGUAGE     Turbo Basic - Version 1.0
REM---------------------------------------------------------------------

start:

REM compute maximum discharge for lateral pipe assuming full pipe flow
TileArea=3.1416*(TileDiameter/12)^2/4
TilePerimeter=3.1416*TileDiameter/12
FullPipeQ=1.486/.015*(TileArea/TilePerimeter)^(2/3)*(TileGrade/100)^.5*Tile
Area
FullPipeQ=FullPipeQ/FinalLspacing*12*24*60*60/TileLength
```

```
units$="FPS"
IF TileDiameter=3 THEN remm=3.5
IF TileDiameter=4 THEN remm=5.1
IF TileDiameter=5 THEN remm=10.0
dz=0.001
dd=1000
ElapsedTime=0

CLS

wtdRain=(siWTdepthLateral+siWTdepthMidpoint)/2-(infiltration/12)/DPorosity*.8

IF wtdRain<0 THEN wtdRain=0
IF WeirDepth>siWTdepthLateral THEN
    DrainTo=siWTdepthLateral+dz
ELSE
    DrainTo=WeirDepth
END IF

REM calculate maximum q for drawdown using hooghoudt equation
m=WeirDepth-wtdRain
l=FinalLspacing
GOSUB convert1
GOSUB qcalc1
IF q>FullPipeQ THEN q=FullPipeQ
MaxQ=q
LOCATE 22,5:PRINT SPACE$(75);
LOCATE 23,5:PRINT SPACE$(75);
LOCATE 24,5:PRINT SPACE$(75);
LOCATE 22,5:PRINT "CALCULATED MAXIMUM DISCHARGE DURING DRAWDOWN IS ";
PRINT USING "#.###";MaxQ;:PRINT " IN/DAY"
anykey$="":LOCATE 23,5
PRINT "DO YOU WANT TO REDUCE THE MAXIMUM DRAWDOWN DISCHARGE (y/n)? ";
WHILE LEN(anykey$)=0:anykey$=INKEY$:WEND
IF anykey$="y" OR anykey$="Y" THEN
   LOCATE 24,5:INPUT "ENTER NEW MAXIMUM DRAWDOWN DISCHARGE (IN/DAY)";MaxQ
END IF
CLS

REM perform calculations for initial flow (0<ldist<FinalSpacing/2)
REM  by incrementing ldist by dd
m=WeirDepth-wtdRain
z=wtdRain
FOR ldist=0 TO FinalLspacing/2 STEP FinalLspacing/2/dd
   IF ldist=0 THEN
      oldarea=(DrainTo-wtdRain)*FinalLSpacing/2
      oldq=0
      oldl=0
      ElapsedTime=0
   ELSE
      area=(3.1416*ldist*(DrainTo-wtdRain))/4+(DrainTo-wtdRain)*_
```

```
            (FinalLSpacing/2-ldist)
        l=ldist*2
        GOSUB convertl
        GOSUB qcalcl
        IF q>sirate+drrate THEN q=sirate+drrate
        IF q>FullPipeQ THEN q=FullPipeQ
        time=(oldarea-area)*2*DPorosity/((oldq+q)/2/24/12*(oldl+l)/2)
        ElapsedTime=ElapsedTime+time
        GOSUB sr1001
        oldarea=area
        oldq=q
        oldl=l
      END IF
NEXT ldist
LOCATE 3,1:PRINT "Phase 1 Elapsed Time: ";:PRINT USING "###";ElapsedTime
REM perform calculations for ldist = FinalLSpacing/2
REM  by varying z  until z =  DrainTo
FOR z=wtdRain TO DrainTo-dz STEP dz
  REM calculate drainage q
  m=WeirDepth-z
  area = (3.1416*FinalLSpacing/2*(DrainTo-z))/4
  l=FinalLSpacing
  GOSUB convertl
  GOSUB qcalcl
  IF q>MaxQ THEN q=MaxQ
  IF q>FullPipeQ THEN q=FullPipeQ
  time=(oldarea-area)*2*DPorosity/((oldq+q)/2/24/12*FinalLSpacing)
  ElapsedTime=ElapsedTime+time
  GOSUB sr1001
  oldarea=area
  oldq=q
NEXT z
LOCATE 21,5:PRINT "FOR LATERAL SPACING = ";:PRINT USING "###";_
   CINT(FinalLspacing);:PRINT " FT. AND MAXIMUM PIPE DISCHARGE = ";:_
   PRINT USING "#.###";MaxQ;:PRINT " IN/HR"
LOCATE 22,5:PRINT "WATER TABLE DRAWDOWN ELAPSED TIME = ";:_
   PRINT USING "####";CINT(ElapsedTime);:PRINT " HRS"
anykey$="":LOCATE 23,5:PRINT "DO YOU WANT TO REVISE LATERAL SPACING (y/n)?
";
WHILE LEN(anykey$)=0:anykey$=INKEY$:WEND
IF anykey$="y" OR anykey$="Y" THEN
   LOCATE 24,5:INPUT "ENTER NEW SPACING (ft)";FinalLSpacing
   GOTO start
END IF
REM=====================================================================
REM      SUBROUTINE NAME          SISUBR.INC
REM      SUBROUTINE AUTHOR P. Gerrish and H. Belcher
REM      DATE OF LAST REVISION   10/06/89
REM      PROGRAM LANGUAGE  Turbo Basic - Version 1.0
REM--------------------------------------------------------------------
        sr100:
                     IF ii%  = 1  THEN
```

```
                    PRINT "MAXIMUM LATERAL SPACING FOR SUBS DRAINAGE = ";
                    PRINT USING "###";CINT(l);:PRINT " ft."
                    ldr=l
          ELSEIF ii% = 2 THEN
                    PRINT "MAXIMUM LATERAL SPACING FOR SUBIRRIGATION = ";
                    PRINT USING "###";CINT(l);:PRINT " ft."
                    lsi=l
                END IF
RETURN


CONVERT:

      IF units$ = "FPS" THEN
            dtm = TileDepth*12*0.0254
            dbm = BarrierDepth*12*0.0254
            lm = l*12*0.0254
            re = remm/1000
            km = k*0.0254*24
            mm = m*12*0.0254
            dwtm = dwt*12*0.0254
      ELSE
            dtm = TileDepth
            dbm = BarrierDepth
            lm = l
            re = remm/1000
            km = k
            mm = m
            dwtm = dwt
      END IF
RETURN

     QCALC:
      doverl = (dbm - dtm)/lm
      a = 3.55 - 1.6*doverl + 2*doverl^2
      IF doverl > 0.3 THEN
            var = lm/re
            dem = lm*(3.14159)/(8*(LOG(var)-1.15))
      ELSE
            dem = (dbm-dtm)/(1+doverl*((8/3.14159)*LOG((dbm-dtm)/re)-a))

      END IF
      de = dem*100/2.54/12
      IF ii% = 1 THEN
            r = (8*km*mm*dem + 4*km*mm^2)/lm^2*1000
      ELSEIF ii% = 2 THEN
            r = 4*km*mm*(dtm-dwtm+dem)*(2-mm/(dbm-dwtm))/lm^2*1000
      END IF
      q = r/25.4
RETURN

FINE:
```

```
        IF (dq-q) > 0.0005 THEN
             WHILE (dq-q) > 0.0005
                  DECR l, 0.1
                  GOSUB CONVERT
                            GOSUB QCALC
             WEND
        ELSEIF (dq-q) < -0.0005 THEN
             WHILE (dq-q) < -0.0005
                  INCR l, 0.1
                  GOSUB CONVERT
                  GOSUB QCALC
             WEND
        END IF
   RETURN

   MFINE:
        IF (dr-r) > 0.0005 THEN
             WHILE (dr-r) > 0.0005
                  DECR l, 0.01
                  GOSUB CONVERT
                  GOSUB QCALC
             WEND
        ELSEIF (dr-r) < -0.0005 THEN
             WHILE (dr-r) < -0.0005
                  INCR l, 0.01
                  GOSUB CONVERT
                  GOSUB QCALC
             WEND
        END IF
   RETURN
REM-------------------------------------------------------------------
   sr1001:
                 LOCATE 1,1
                 PRINT "DISCHARGE RATE  = ";
                 PRINT USING "#.###";q;:PRINT " in/day";
                 PRINT "  AT TIME = ";
                 PRINT USING "####";CINT(ElapsedTime);:PRINT " hr";
                 PRINT "  AT WT DEPTH = ";
                 PRINT USING "##.##";z;:PRINT " ft"
             RETURN


   convert1:
            IF units$ = "FPS" THEN
              dtm = TileDepth*12*0.0254
              dbm = BarrierDepth*12*0.0254
              lm = l*12*0.0254
                   re = remm/1000
              km = k*0.0254*24
                     mm = m*12*0.0254

            ELSE
```

```
                dtm = TileDepth
                dbm = BarrierDepth
                lm = 1
                re = remm/1000
                km = k
                    mm = m
                     END IF
        RETURN

   qcalc1:
        doverl = (dbm - dtm)/lm
        a = 3.55 - 1.6*doverl + 2*doverl^2
        IF doverl > 0.3 THEN
              var = lm/re
              dem = lm*(3.14159)/(8*(LOG(var)-1.15))
        ELSE
              dem  =  (dbm-dtm)/(1+doverl*((8/3.14159)*LOG((dbm-dtm)/re)  -
a))
        END IF
        de = dem*100/2.54/12
              r = (8*km*mm*dem + 4*km*mm^2)/lm^2*1000
        q = r/25.4
   RETURN
REM=================================================================
REM   SUBROUTINE NAME            SIOUTPUT.INC
REM   SUBROUTINE AUTHOR    H. Belcher, MSU
REM   DATE OF LAST REVISION      10/13/89
REM   PROGRAM LANGUAGE           Turbo Basic - Version 1.0
REM-----------------------------------------------------------------
CLS
PRINTAB(10);"**********************************************************"

PRINT TAB(10);"              S I L S P A C E   R E S U L T S
"
PRINT TAB(10);"                Michigan State University
"
PRINTAB(10);"**********************************************************"

X%=8
PRINT TAB(X%)"FOR:"
PRINT TAB(X%);"Depth to the lateral pipe (ft)............ ";
PRINT USING "##.##";TileDepth
PRINT TAB(X%);"Diameter of the lateral pipe (in).........    ";
PRINT USING "##";TileDiameter
PRINT TAB(X%);"Minimum grade of the lateral pipe (%)...... ";
PRINT USING "#.###";TileGrade
PRINT TAB(X%);"Length of the lateral pipe (ft)..........  ";
PRINT USING "####";TileLength
PRINT TAB(X%);"For Subirrigation:
PRINT TAB(X%);" Depth to water table at lateral (ft)...... ";
PRINT USING "##.##";siWTdepthLateral
PRINT TAB(X%);" Depth to water table at midpoint (ft)..... ";
```

```
PRINT USING "##.##";siWTdepthMidpoint
PRINT TAB(X%);"For Subsurface Drainage:
PRINT TAB(X%);"  Depth to water table at lateral (ft)..... ";
PRINT USING "##.##";sdWTdepthLateral
PRINT TAB(X%);"  Depth to water table at midpoint (ft).... ";
PRINT USING "##.##";sdWTdepthMidpoint
PRINT TAB(X%);"Design subirrigation rate (in/day).........  ";
PRINT USING "#.##";sirate
PRINT TAB(X%);"Design subsurface drainage rate (in/day)...  ";
PRINT USING "#.##";drrate
PRINT TAB(X%);"Design storm rainfall (in)................. ";
PRINT USING "##.##";rainfall
PRINT TAB(X%);"SCS runoff curve number...................   ";
PRINT USING "###";rcn
PRINT TAB(X%);"Design weir depth during drawdown (ft).....  ";
PRINT USING "#.##";WeirDepth
PRINT TAB(X%);"Depth to Barrier (ft).....................  ";
PRINT USING "##.#";BarrierDepth
PRINT TAB(X%);"Saturated hydraulic conductivity (in/hr)...  ";
PRINT USING "#.##";k
PRINT TAB(X%);"Saturated - Drained Upper Limit............  ";
PRINT USING "#.##";DPorosity
anykey$="":WHILE LEN(anykey$)=0:anykey$=INKEY$:WEND
CLS
PRINT TAB(X%)"RESULTS:"
PRINT TAB(X%)"Maximum lateral spacing for subirrigation (ft)...   ";
PRINT USING "###";lsi
PRINT TAB(X%)"Maximum lateral spacing for subs. drainage (ft)..   ";
PRINT USING "###";ldr
PRINT TAB(X%)"For lateral spacing (ft)........................   ";
PRINT USING "###";FinalLspacing
PRINT TAB(X%)"Time to return to subirrigation WTD (hr).........  ";
PRINT USING "####";ElapsedTime
PRINT TAB(X%)"Following precipitation with infiltration (in)...  ";
PRINT USING "#.##";infiltration
PRINT TAB(X%)"Water table depth after precipitation (ft)....... ";
PRINT USING "##.##";wtdRain
PRINT TAB(X%)"Maximum discharge for drawdown (in/day).......... ";
PRINT USING "#.###";MaxQ;
REM-----------------------------------------------------------------------
---
LOCATE 23,8
anykey$=""
PRINT "DO YOU WANT A PRINTOUT (y/n)? ";
WHILE LEN(anykey$)=0:anykey$=INKEY$:WEND
IF anykey$="y" OR anykey$="Y" THEN
                          L     P     R     I     N     T
TAB(10);"*************************************************************"
  LPRINT TAB(10);"                S I L S P A C E   R E S U L T S
  "
  LPRINT TAB(10);"                  Michigan State University
  "
```

```
                              L        P        R        I        N        T
TAB(10);"************************************************************"
   X%=12
   LPRINT
   LPRINT TAB(X%)"FOR:"
   LPRINT
   LPRINT TAB(X%);"Depth to the lateral pipe (ft)............. ";
   LPRINT USING "##.##";TileDepth
   LPRINT TAB(X%);"Diameter of the lateral pipe (in)..........    ";
   LPRINT USING "##";TileDiameter
   LPRINT TAB(X%);"Minimum grade of the lateral pipe (%)...... ";
   LPRINT USING "#.###";TileGrade
   LPRINT TAB(X%);"Length of the lateral pipe (ft)............  ";
   LPRINT USING "####";TileLength
   LPRINT TAB(X%);"For Subirrigation:
   LPRINT TAB(X%);" Depth to water table at lateral (ft)...... ";
   LPRINT USING "##.##";siWTdepthLateral
   LPRINT TAB(X%);" Depth to water table at midpoint (ft)..... ";
   LPRINT USING "##.##";siWTdepthMidpoint
   LPRINT TAB(X%);"For Subsurface Drainage:
   LPRINT TAB(X%);"  Depth to water table at lateral (ft)..... ";
   LPRINT USING "##.##";sdWTdepthLateral
   LPRINT TAB(X%);"  Depth to water table at midpoint (ft).... ";
   LPRINT USING "##.##";sdWTdepthMidpoint
   LPRINT TAB(X%);"Design subirrigation rate (in/day).........  ";
   LPRINT USING "#.##";sirate
   LPRINT TAB(X%);"Design subsurface drainage rate (in/day)...  ";
   LPRINT USING "#.##";drrate
   LPRINT TAB(X%);"Design storm rainfall (in)................. ";
   LPRINT USING "##.##";rainfall
   LPRINT TAB(X%);"SCS runoff curve number...................   ";
   LPRINT USING "###";rcn
   LPRINT TAB(X%);"Design weir depth during drawdown (ft).....  ";
   LPRINT USING "#.##";WeirDepth
   LPRINT TAB(X%);"Depth to Barrier (ft).....................  ";
   LPRINT USING "##.#";BarrierDepth
   LPRINT TAB(X%);"Saturated hydraulic conductivity (in/hr)...  ";
   LPRINT USING "#.##";k
   LPRINT TAB(X%);"Saturated - Drained Upper Limit............  ";
   LPRINT USING "#.##";DPorosity
   LPRINT
   LPRINT TAB(X%)"RESULTS:"
   LPRINT
   LPRINT TAB(X%)"Maximum lateral spacing for subirrigation (ft)...   ";
   LPRINT USING "###";lsi
   LPRINT TAB(X%)"Maximum lateral spacing for subs. drainage (ft)..   ";
   LPRINT USING "###";ldr
   LPRINT TAB(X%)"For lateral spacing (ft)........................   ";
   LPRINT USING "###";FinalLspacing
   LPRINT TAB(X%)"Time to return to subirrigation WTD (hr).........  ";
   LPRINT USING "####";ElapsedTime
   LPRINT TAB(X%)"Following precipitation with infiltration (in)...  ";
```

```
    LPRINT USING "#.##";infiltration
    LPRINT TAB(X%)"Water table depth after precipitation (ft)....... ";
    LPRINT USING "##.##";wtdRain
    LPRINT TAB(X%)"Maximum discharge for drawdown (in/day).......... ";
    LPRINT USING "#.###";MaxQ
    FOR i%=1 TO 31:LPRINT:NEXT i%
END IF
CLS
anykey$=""
PRINT "DO YOU WANT TO QUIT (y/n)? ";
WHILE LEN(anykey$)=0:anykey$=INKEY$:WEND
IF anykey$="y" OR anykey$="Y" THEN
    CLS
    END
ELSE
    CLEAR
    GOTO begin
END IF
```

```
REM============================================================================
REM   PROGRAM NAME          SIECON.BAS
REM   PROGRAM AUTHOR        H. Belcher, MSU
REM   DATE OF LAST REVISION       10/17/89
REM   PROGRAM LANGUAGE            Turbo Basic - Version 1.0
REM---------------------------------------------------------------------------
CLS
P                    R                    I                    N                    T
TAB(3);"**********************************************************************
****"
PRINT
PRINT TAB(3);"      SIECON: An economic analysis program for water table
management     "
PRINT
P                    R                    I                    N                    T
TAB(3);"**********************************************************************
****"
PRINT
PRINT
PRINT
PRINT TAB(28);"      H. W. Belcher       "
PRINT TAB(28);"MICHIGAN STATE UNIVERSITY"
PRINT TAB(28);"      Version: 1.01       "
PRINT TAB(28);"        09/29/89           "
LOCATE 24,26
PRINT "PRESS ANY KEY TO CONTINUE? ";
WHILE LEN(anykey$)=0
   anykey$=INKEY$
WEND

begin:

REM---------------------input data---------------------------
CLS
anykey$=""
PRINT "WILL INPUT DATA COME FROM DISKFILE (f) OR KEYBOARD (k)? "
WHILE LEN(anykey$)=0:anykey$=INKEY$:WEND
IF anykey$="F" OR anykey$="f" THEN
   INPUT "Enter input file name ................ ";FileName$
   CLS
   OPEN FileName$ FOR INPUT AS #1
   INPUT #1,P,A,L,i,area,YldWO,YldW,ProdCostWO,ProdCostW,Price
   CLOSE #1
   REM------------------------------------------------------------------------
ELSE
   PRINT
   INPUT "Enter estimated installation cost of the system ($).... ";P$
   IF LEN(P$)=0 THEN P=INSTAL ELSE P=VAL(P$)
   INPUT "Enter estimated cost of maintaining the system ($)..... ";A$
   IF LEN(A$)=0 THEN A=ANN ELSE A=VAL(A$)
   INPUT "Enter expected life of the system (yr)................. ";L$
   IF LEN(L$)=0 THEN L=LIFE ELSE L=VAL(L$)
```

```
   INPUT "Enter minimum attractive rate of return (%)........... ";i$
   IF LEN(i$)=0 THEN i=RATE ELSE i=VAL(i$)
   INPUT "Field size (area).................................... ";area$
   IF LEN(area$)=0 THEN area=SIZE ELSE area=VAL(area$)
   INPUT "Enter estimated yield w/o system (vol/unit area)....... ";YldWO$
   IF LEN(YldWO$)=0 THEN YldWO=YIELD1 ELSE YldWO=VAL(YldWO$)
   INPUT "Enter estimated yield w/ system (vol/unit area)........ ";YldW$
   IF LEN(YldW$)=0 THEN YldW=YIELD2 ELSE YldW=VAL(YldW$)
   INPUT "Enter production cost w/o system ($/unit area).........
";ProdCostWO$
   IF LEN(ProdCostWO$)=0 THEN ProdCostWO=COST1 ELSE
ProdCostWO=VAL(ProdCostWO$)
   INPUT "Enter production cost w/ system ($/unit area)..........
";ProdCostW$
   IF LEN(ProdCostW$)=0 THEN ProdCostW=COST2 ELSE ProdCostW=VAL(ProdCostW$)
   INPUT "Enter expected product market price ($/unit vol)....... ";Price$
   IF LEN(Price$)=0 THEN Price=VALUE ELSE Price = VAL(Price$)
END IF

REM-----------------------------------------------------------------

INSTAL=P
ANN=A
LIFE=L
RATE=i
SIZE=area
YIELD1=YldWO
YIELD2=YLDW
COST1=ProdCostWO
COST2=ProdCostW
VALUE=Price
REPL=0


AINSTAL=INSTAL*((RATE/100)*(1+RATE/100)^(LIFE)/((1+RATE/100)^(LIFE)-1))
ANNUAL = AINSTAL+ANN-(REPL*(RATE/100)/((1+RATE/100)^(LIFE)-1))
INCREASE = SIZE*(YIELD2*VALUE-YIELD1*VALUE)-SIZE*(COST2-COST1)
RTN=INCREASE/ANNUAL

CLS
PRINT TAB(8);"***************************************************************"
PRINT TAB(8);"                 S I E C O N   R E S U L T S                  "
PRINT TAB(8);"                  Michigan State University                    "
PRINT TAB(8);"***************************************************************"
X%=8
PRINT
PRINT TAB(X%)"FOR:"
PRINT TAB(X%);"Estimated installation cost of the system ($)..... ";
PRINT USING "#######";P
PRINT TAB(X%);"Cost of operating and maintaining the system ($).. ";
PRINT USING "#######";A
PRINT TAB(X%);"Expected life of the system (yr)................. ";
```

```
PRINT USING "#######";L
PRINT TAB(X%);"Minimum attractive rate of return (%)............ ";
PRINT USING "####.##";i
PRINT TAB(X%);"Field size (area)................................ ";
PRINT USING "#######";area
PRINT TAB(X%);"Estimated yield w/o system (vol/unit area)........ ";
PRINT USING "#######";YldWO
PRINT TAB(X%);"Estimated yield w/ system (vol/unit area)......... ";
PRINT USING "#######";YldW
PRINT TAB(X%);"Production cost w/o system ($/unit area).......... ";
PRINT USING "####.##";ProdCostWO
PRINT TAB(X%);"Production cost w/ system ($/unit area)........... ";
PRINT USING "####.##";ProdCostW
PRINT TAB(X%);"Expected product market price ($/unit vol)........ ";
PRINT USING "####.##";price
PRINT
PRINT TAB(X%);"RESULTS:"
PRINT TAB(X%);"TOTAL INSTALLATION COST...........................";
PRINT USING "$$######";INSTAL+.5
PRINT TAB(X%);"TOTAL ANNUAL SYSTEM COST..........................";
PRINT USING "$$######";ANNUAL+.5
PRINT TAB(X%);"TOTAL ANNUAL INCREASE IN"
PRINT TAB(X%);"INCOME DUE TO SYSTEM..............................";
PRINT USING "$$######";INCREASE+.5
PRINT TAB(X%);"BENEFIT/COST RATIO................................";
PRINT USING "#####.##";RTN+.005
REM-----------------------------------------------------------------
---
LOCATE 25,8
anykey$=""
PRINT "DO YOU WANT A PRINTOUT (y/n)? ";
WHILE LEN(anykey$)=0:anykey$=INKEY$:WEND
IF anykey$="y" OR anykey$="Y" THEN
   LPRINT
                          L       P       R       I       N       T
TAB(12);"************************************************************"
   LPRINT TAB(12);"                  S I E C O N   R E S U L T S
 "
   LPRINT TAB(12);"                  Michigan State University
   "
                          L       P       R       I       N       T
TAB(12);"************************************************************"
   X%=12
   LPRINT
   LPRINT TAB(X%)"FOR:"
   LPRINT TAB(X%);"Estimated installation cost of the system ($)..... ";
   LPRINT USING "#######";P
   LPRINT TAB(X%);"Cost of operating and maintaining the system ($).. ";
   LPRINT USING "#######";A
   LPRINT TAB(X%);"Expected life of the system (yr)................. ";
   LPRINT USING "#######";L
   LPRINT TAB(X%);"Minimum attractive rate of return (%)............ ";
```

```
   LPRINT USING "####.##";i
   LPRINT TAB(X%);"Field size (area)............................... ";
   LPRINT USING "#######";area
   LPRINT TAB(X%);"Estimated yield w/o system (vol/unit area)........ ";
   LPRINT USING "#######";YldWO
   LPRINT TAB(X%);"Estimated yield w/ system (vol/unit area)......... ";
   LPRINT USING "#######";YldW
   LPRINT TAB(X%);"Production cost w/o system ($/unit area).......... ";
   LPRINT USING "####.##";ProdCostWO
   LPRINT TAB(X%);"Production cost w/ system ($/unit area)........... ";
   LPRINT USING "####.##";ProdCostW
   LPRINT TAB(X%);"Expected product market price ($/unit vol)........ ";
   LPRINT USING "####.##";price
   LPRINT
   LPRINT TAB(X%);"RESULTS:"
   LPRINT TAB(X%);"TOTAL INSTALLATION COST...........................";
   LPRINT USING "$$#######";INSTAL+.5
   LPRINT TAB(X%);"TOTAL ANNUAL SYSTEM COST..........................";
   LPRINT USING "$$#######";ANNUAL+.5
   LPRINT TAB(X%);"TOTAL ANNUAL INCREASE IN"
   LPRINT TAB(X%);"INCOME DUE TO SYSTEM..............................";
   LPRINT USING "$$#######";INCREASE+.5
   LPRINT TAB(X%);"BENEFIT/COST RATIO................................";
   LPRINT USING "#####.##";RTN+.005
   FOR i%=1 TO 42:LPRINT:NEXT i%
END IF

CLS

anykey$=""
PRINT "DO YOU WANT TO QUIT (y/n)? ";
WHILE LEN(anykey$)=0:anykey$=INKEY$:WEND
IF anykey$="y" OR anykey$="Y" THEN
   CLS
   END
ELSE
   GOTO begin
END IF

END
```

APPENDIX G

WATER TABLE MANAGEMENT SYSTEM DESIGN EXAMPLE

Design a soybean subirrigation system for 39 acre field located NE of St. Johns, Michigan. Field studies of subirrigated soybean production suggests that soybean yield is related to the depth and fluctuation of the water table by the linear regression equation relative soybean yield = 89.9 - 2.30 * wfi where wfi is the wet stress fluctuation index for June through August.

The soil at the site is Ziegenfuss clay loam with a dense clay layer at 5.5 ft depth practically impervious to water. A site investigation indicates the soil above the dense clay layer has the following properties:

depth (in)	k (in/h)	sat (in/in)	dul (in/in)
0 - 9	1.6	.45	.30
9 - 15	0.2	.42	.27
15 - 66	0.7	.44	.29

where: depth = depth below soil surface, in
k = saturated lateral hydraulic conductivity, in/hr
sat = volumetric water content at saturation, in/in
dul = volumetric water content at drained upper limit, in/in

Daily rainfall record near the site are available from a National Weather Service Cooperative observer station at St. Johns. The SIRAIN output using those records for the June, July and August months follow:

MONTH	2 YR RAIN (in)	2 YR EVENTS	10 YR RAIN (in)
JUN	0.16	10	0.91
JUL	0.15	8	0.77
AUG	0.20	8	0.96
SEASON	0.16	28	0.83

Next, three subirrigation system design alternatives were investigated using the computer model SILSPACE. For the three alternatives, the lateral spacing to provide steady state subsurface drainage and subirrigation is held constant. The only parameter varied for each alternative is the maximum discharge during drawdown following the .16 in design rainfall. That discharge was set equal to 0.375 in./day for alternate 1, 0.500 in./day for alternate 2 and 0.750 in./day for alternate 3.

The input data for the alternates:

Depth to the lateral pipe (ft)............. 4.00
Diameter of the lateral pipe (in).......... 4
Minimum grade of the lateral pipe (%)......0.050
Length of the lateral pipe (ft)............ 300
For Subirrigation:
Depth to water table at lateral (ft)...... 1.50
Depth to water table at midpoint (ft)..... 2.00
For Subsurface Drainage:
Depth to water table at lateral (ft)..... 4.00
Depth to water table at midpoint (ft).... 2.00
Design subirrigation rate (in/day)......... 0.30
Design storm rainfall (in)................. 0.16
Design storm occurences.................... 28
SCS runoff curve number.................... 82
Total time (days).......................... 90
Design weir depth during drawdown (ft)..... 4.00

produced the following results:

Maximum lateral spacing for subirrigation (ft)... 27, 27, 27
Maximum lateral spacing for subs. drainage (ft).. 40, 34, 27
For lateral spacing (ft)......................... 27, 27, 27
Time to return to subirrigation WTD (hr)......... 27, 36, 42
Following precipitation with infiltration (in)... 0.16, 0.16, 0.16
Water table depth after precipitation (ft)....... 1.46, 1.46, 1.46
Water table depth after drawdown (ft)............ 1.61, 1.61, 1.61

for:

Maximum discharge for drawdown (in/day).......... .375, .500, .750

The results of each SILSPACE simulation follow:

DESIGN ALTERNATE		1	2	3
EVALUATION PERIOD		season	season	season
EVALUATION PERIOD	days	90	90	90
RAINFALL	in	0.16	0.16	0.16
EVENTS DURING EVAL		28	28	28
DRAWDOWN TIME	hr	42	36	27
DEPTH TO HIGH WT	ft	1.46	1.46	1.46
DEPTH TO LOW WT	ft	1.61	1.61	1.61
DEPTH TO MEAN WT	m	1.58	1.59	1.59
wfi	m*hr	1.57	2.68	3.54

Substituting the parameters wfi parameter into the Bannister site soybean yield regression equation resulted in:

DESIGN ALTERNATE	1	2	3
syld=89.9-2.30wfi	82%	84%	86%

The preceding indicates increasing the subirrigation maximum discharge capacity to .375, .500 and .750 in/day will result in a soybean relative yield increase of 82, 84 and 86% respectively. Assuming a 100% relative yield is 65 bu/ac this translates to a yield of 57, 58, and 59 bu/ac for design alternative 1, 2 and 3 respectively. Thus to maximize yield, the third design alternative is best, ie. design the mains and submains to handle a flow rate of 0.750 inches/day.

However, to optimize the economic efficiency of the system to produce soybean yield costs of the alternatives must be considered. Detail design of each alternate resulted in the following system quantities and estimated installation costs:

COST OF SUBMAINS

	unit price	dc=.375 lf	dc=.375 $	dc=.500 lf	dc=.500 $	dc=.750 lf	dc=.750 $
5"	.79	1188	939	918	725	594	469
6"	1.11	729	809	648	719	324	360
8"	2.14	1080	2311	1107	2369	999	2138
10"	3.37			324	1092	756	2548
12"	4.25					324	1377
TOTAL		2997	4059	2997	4905	2997	6891

COST OF MAINS

	unit price	dc=.375 lf	dc=.375 $	dc=.500 lf	dc=.500 $	dc=.750 lf	dc=.750 $
5"	.79						
6"	1.11	350	389				
8"	2.14			350	749	350	749
10"	3.37	400	1348				
12"	4.25	15	64	400	1700		
15"	5.91			15	89	400	2364
18"	7.25					15	109
TOTAL		765	1800	765	2538	765	3222

COST OF LATERALS

	unit price	dc=.375 lf	dc=.375 $	dc=.500 lf	dc=.500 $	dc=.750 lf	dc=.750 $
	.47	25913	12179	25913	12179	25913	12179
MISC COSTS			13000		13000		13000
GRAND TOTAL			31038		32622		35292

The detailed design and cost estimate for each alternate indicates:

Alternate 1 will cost <u>$31038</u> and provide a <u>57 bu/ac</u> annual yield.

Alternate 2 will cost <u>$32622</u> and provide a <u>58 bu/ac</u> annual yield.

Alternate 3 will cost <u>$35292</u> and provide a <u>59 bu/ac</u> annual yield.

To determine the most economic efficient alternative the computer module SIECON is used to calculate the benefit/cost ratio of each of the three alternatives.

Using an estimated annual operating and maintenance expense equal to $500 per year, an expected system life of 20 years, a minimum attractive interest rate of 8%, a 35 bu/ac estimated yield without the system, a without system production cost of $110.00 per acre, a with system production cost of $120.00 per acre and an expected market price of $6.50 per bushel of soybeans, the SIECON economic analysis provides the following results:

	alt 1	alt 2	alt 3
Annual System Cost	$3662	$3823	$4095
Annual Increase in Income	$4124	$4325	$4527
Benefit/Cost Ratio	1.13	1.14	1.11

Thus the analysis indicates the second design alternate is the most economic efficient alternative of the three.

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