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COMPARATIVE ANALYSIS OF THE EFFECT OF A CLOSED-LOOP IRRIGATION SYSTEM ON CROP YIELD

A THESIS

Presented to

The Faculty of the Division of Graduate

Studies and Research

by

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In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Industrial Engineering

Georgia Institute of Technology

April, 1971

COMPARATIVE ANALYSIS OF THE EFFECT OF A CLOSED-LOOP

IRRIGATION SYSTEM ON CROP YIELD

Approved:

Chairman

Date approved by Chairman: 14 April 1971

ACKNOWLEDGMENTS

The author wishes to express his sincere appreciation for the valuable guidance, criticism, and encouragement given by Professor Leslie G. Callahan, Jr., who served as thesis advisor and committee chairman.

Appreciation is extended to my Thesis Committee, Dr. David E. Fyffe and Mr. John R. Carreker, for their constructive criticism and encouragement throughout the course of my research.

To my wife, Nancy, a very special debt for her continuous encouragement, patience, and understanding during my graduate study.

To my children, Elisabeth, Katherine, and John Charles, a special "Thank You" for their devotion, love, and understanding.

To my typist, Mrs. Lydia Geeslin, my sincere appreciation for her assistance in preparing this manuscript and the excellent typing job.

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SUMMARY

This thesis tests the hypothesis that an irrigation system operating in response to devices that sense crop needs for water through measurement of the soil moisture content can more effectively meet those needs in excess of rainfall than any other system in use in the state of Georgia. A comparative analysis of three field moisture systems, natural rainfall, manual irrigation, and a closed-loop irrigation system, is made using a six year period of simulated growth for each of four high-value crops grown in Georgia. Estimated yields obtained from individual crop production functions, which were derived by multiple regression analysis of empirical test data, are the basis from which the analysis is made.

The results of the simulation indicate there is a significant improvement in crop yield when the crop production system is subjected to a more efficiently controlled moisture level input provided by rainfall and a closed-loop irrigation system. The study also underscores the importance of the farmer's need for knowing when to irrigate and how much water to apply.

CHAPTER I

INTRODUCTION

Background

Systems engineering has, over the past twenty years, been influential in developing a methodology directed mainly at the solution of complex technological problems associated with national defense, space research, and industrial production. This methodology has evolved from operations research techniques, applied mathematics, probability and statistics, econometrics, and the vast science of computers. The success in applying this methodology has stimulated increased work in its application to other areas such as health systems, urban-development, bioengineering and, to a very limited extent, agriculture (1).

Recent research concerning the state of agriculture systems engineering techniques and methodologies indicates that they are applicable to Georgia farming and have been used to a very limited extent in the state. At present, Georgia agricultural systems analysis is under-developed, under-nourished, and newly emerging in its efforts to be of service to a vast section of the state economy whose technology in cost control and management is lagging that of other industries. According to Dean Henry W. Garren (2) of the University of Georgia College of Agriculture, Georgia is rapidly expanding in its role as a supplier of agricultural products. Since 1950, the value of commercial farm products has almost doubled in spite of the unfavorable price trends. The output from Georgia farms has increased nearly twice as fast percentage wise as that of the Nation as a whole. Farming in the future will have extremely important economic implications. At present, the most modest commercial farm represents an investment of nearly $60,000. More elaborate family farming enterprises have upwards of $100,000 invested. There are operations, such as the Vantress Poultry Farms in Georgia, and some farms in California's Imperial Valley, which represent million-dollar investments. As farm operations grow and the dependence on more and better machinery and production methods increases, the need to effectively transfer systems technology to the farm and its operation becomes more apparent. Considering the increasing demand for agricultural products with a greater requirement for improved technology, the farms of the future will be more expensive to operate, just as they must be more productive.

The farm of the future is the object of considerable speculation. Dr. George W. Irving, Jr., Administrator of the Agricultural Research Service, USDA, has described the farm of the future as follows:

> Agriculture will be highly specialized. Farms in one area will concentrate on growing oranges; those in another area, tomatoes; in another potatoes - capitalizing on the competitive advantage of soil or climate given for a particular crop....
> Sensors buried in the soil will tell him (the farmer) when his plants need water, and automated irrigation systems will bring it to them.... Such things sound fantastic, but already they exist in pilot form or in the research stage (3).

Crop Production System

Water is not the only variable which affects the yield of crops grown in a given field. In systems terminology, crops can be considered as processors which are subjected to several controllable and uncontrollable input variables with yield as the output variable. Figure 1 represents this open-end production system.

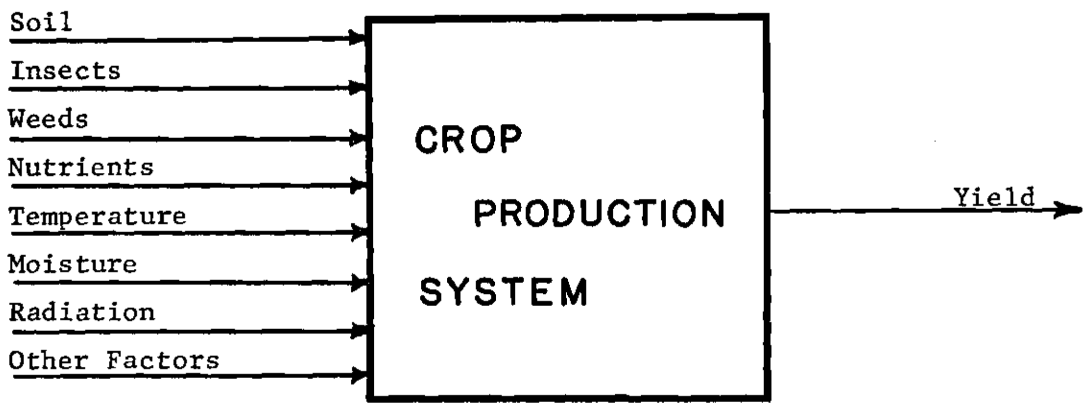

Figure 1. An Open-End Crop Production System

The effects of these variables on crops and the corresponding output are the subject of continuing research. Studies are being conducted to determine how best to control the effects of many of these variables on crops and to establish controls which will effectively result in improved crop yields. However, one of the greatest problems in increasing yield from a given crop deals with the maintenance of an adequate moisture level for the crop during various stages of growth. It is the consideration of the effects of this single factor on crop growth and subsequent yield which serves as the foundation of this research project.

Limits on Water

Crop specialization and an increase in productivity of crops will demand a corresponding increase in the need for water to fulfill the requirements for more efficient crop growth and development. Since water demands are not limited solely to agriculture, the establishment of priorities for water use may be necessary to insure availability. The day is fast approaching in this nation when only the most efficient and productive uses of water will be accepted. Agriculture with its constant demand for safe water will not be excluded from such a requirement. Irrigation and water management must be analyzed to learn how to get the most efficient use of water to obtain maximum production from each unit of water, each unit of land, and each unit of labor and other production inputs.

Dean Garren also pointed out,

> one of our most urgent needs is to develop irrigation systems to tap the tremendous underground water supply of South Georgia. We need only to find economical ways to use this water. Crop yields can be increased by as much as four to six times by irrigation...(4).

As an example, the trend toward intensified agriculture with corn yields in excess of 300 bushels per acre will require huge water supplies applied at the proper time in the correct amount. To accomplish this, the use of sensors to measure the soil moisture content accurately or to measure the moisture needs directly from the plant will be vital to the operation of an automated irrigation system specifically designed for the area and built to operate when the crop needs water to supplement the natural rainfall in the area.

Importance of the Problem

Irrigation of commercial crops in Georgia is still considered a relatively new agricultural practice by many people. However, a recent survey (5) of the use of irrigation by Georgia farmers was conducted by the Cooperative Extension Service, University of Georgia College of Agriculture. The results of this survey indicated that the use of irrigation systems is rapidly increasing. The 1951 survey indicated there were a total of 314 irrigation systems in the state irrigating about 9500 acres. By 1960, the number of systems was 2549 for an acreage of 98,133. The survey taken in June, 1970, recorded 6572 systems providing water by irrigation for a total irrigated acreage of 144,629. Thus it appears that Georgia farmers are recognizing the fact that an inadequate frequency and distribution of rainfall during the growing season usually results in reduced yields and can cause crop failure. They also realize that an adequate irrigation system can often supplement the rainfall during the growing season to their economic advantage. The benefits from irrigation must increase farm income sufficiently to cover the cost of installation, operation, and maintenance and give a reasonable return on capital invested. However, these benefits cannot be realized unless the irrigation system produces water for the crop when the plants need it and in the amount needed.

Research Objective

The purpose of this research is to test the hypothesis that an irrigation system operating in response to devices that sense the crop needs for water can more effectively meet those needs in excess of rainfall than any other system in use in Georgia. Results of this study should show a significant increase in crop yield when subjected to a more efficiently controlled moisture level input provided by a closed-loop irrigation system.

CHAPTER II

LITERATURE SURVEY

Agricultural change in response to continued economic growth and changes in the relative price and productivity of capital and labor will be more rapid in the future. As a result, the day is fast approaching when only the most efficient and productive uses of water will be tolerated (6). Water has become universally accepted as a national resource which must be conserved and used with efficiency if it is to continue to meet the ever increasing demands placed upon it as the economy and population grow.

Crop production is affected significantly by water supply, the availability of plant nutrients, the control of plant insects and diseases, the control of weeds, and other cultural practices. In some parts of the United States, there is insufficient rainfall for crop production, and successful farming and economical yields are achieved only because water is supplied by irrigation. In other parts of the U.S., such as in Georgia, the water supply for maximum plant growth is not adequate because of the significant variation in precipitation. Irrigation and water management then become the principal factors in securing satisfactory crop yields when other production factors are not limiting (7).

Need for Automation

Automation of irrigation systems is recognized as a means of saving water and improving water management on the farm. While more research and study are being directed to development of these systems, the prime reason for their lack of existence on a large scale in the past was due to the absence of economical equipment and efficient design criteria necessary for meeting the practical requirements of automated systems (8). For example, prior to 1950 the goal of good irrigation could not be met easily because the simple method of telling the farmer when and how much to irrigate was not available. Since the early 1960's, devices and techniques have been introduced as aids in water-potential measurement which in turn have led to an increased number of farms being "scientifically" irrigated (9).

Up to now most of the practical use of irrigation systems has been with strictly mechanized systems, or more recently, the auto-mechanized systems. The mechanized or manual system is one requiring a substantial amount of manual labor to move the system and prepare it for use at a given time and place. Operation of such a system requires the farmer to be concerned not only with how and when to move it but when to turn the system on or off. Guides and techniques such as the USDA Soil Conservation Service's Conservation Irrigation Guide for Design of Sprinkler Irrigation Systems (10) or the "bookkeeping method" aid the farmer in operating his irrigation system. These methods require the farmer to know the amount of water the soil holds, how much moisture the plants use, and the amount of water lost by evapotranspiration each day, in order to determine when to irrigate (11). This accounting requires timeliness and a procedure not followed normally in a farmer's way of doing things. Therefore, he might not exercise the degree of diligence needed for this bookkeeping system to be of value to him at the very time the information it provides is needed.

Auto-mechanization

Other systems being used to a great extent are the auto-mechanized systems. First, it might be well to define what is meant by auto-mechanization. The word is intended to embrace automation, mechanization, or any combination of these terms. This includes virtually all the labor-saving activities related to irrigation, be they mechanization only or the implication of a decision making capability associated with automation. According to the definition, if the mechanized operation is automated, the result is auto-mechanization (12).

To date, most of the auto-mechanized systems have been associated with surface and sprinkler irrigation systems. While significant improvements have been made in their design and operation, they have not yet met one of the most important requirements of the complete auto-mechanized systems--that is to operate satisfactorily and efficiently with a minimum of labor, care, and maintenance (13). It is recognized that auto-mechanization of surface irrigation is competing with other automated methods of water application, but in the state of Georgia such systems do not have the capability of being widely used because of the terrain configuration. Rough topography and shallow soils make it difficult to level or grade for surface irrigation. It requires a tremendous land development effort to condition the soil for such a system. The use of the sprinkler or solid set system is much more desirable in this state.

Meteorological Considerations

One of the most advanced approaches presently available for dealing with irrigation scheduling has been developed by Dr. M. E. Jensen, et al. (14). This irrigation scheduling program has been used by the Bureau of Reclamation, irrigation districts, and private consultants and has met with wide acceptance in the West. The basis of the technique relies on adaptation of meteorological data to forecast the next date of irrigation. By maintaining a water budget, the program is able to estimate the number of days until the soil water depletion reaches an optimum value. The next irrigation is then determined by using an evapotranspiration rate based on a 6-day average occurring at the time of the forecast. Since this program was designed primarily for arid and semi-arid regions of the United States, it assumes no additional precipitation before the next irrigation. Adapting this program to sub-humid and humid areas, such as Georgia, would require a more stable forecast of evapotranspiration and the inclusion of rainfall probability. Jensen has made modifications in his original program to allow for the inclusion of precipitation probability and the effects of a long-time average evapotranspiration rate (15). However, the program has not been applied to the intended regions except in a simulation role.

The Improved Irrigation System

While this meteorological approach to irrigation scheduling is a vast improvement over many other methods and does remove much of the guesswork involved with irrigation scheduling, it still lacks the overall efficiency of an automated closed-loop system. This type of system, and the foundation for this thesis, has been proposed by Lawrence R. Swarner, U. S. Department of the Interior, Bureau of Reclamation (16). If an analysis could be made of the irrigation systems of the future, it would reveal irrigation systems which are controlled by moisture sensing devices installed at selected field sites to determine when and where water is needed and how much to apply. Electronic devices would activate the water control valves to allow water delivery and then shut down the system when sensors determine the optimum moisture level is reached. The time and quantity of water application may not be determined by sensors alone but by data from computation of consumptive use, meteorological information, or some other criteria. Such information may be fed into an automatic data processing digital computer which has previously stored input on soil characteristics, plant type, and other factors affecting quantity and timing of irrigation. Electronic control devices then take over and provide the crop with the necessary water application. This automated system can be used for surface irrigation, for sprinkler irrigation, or, to some extent, for subsurface irrigation.

Current Research

According to Maurice N. Langley (17), a wide range of research covering automation of on-farm irrigation has been conducted in recent years at a number of state universities and key stations of the Agricultural Research Service (ARS), USDA. Current research includes work by A. S. Humphreys at the Snake River Conservation Research Center, ARS, Kimberly, Idaho, on systems design and automation of surface irrigation systems; by Drs. H. R. Haise and E. G. Kruse of the Northern Plains Branch, ARS, Fort Collins, Colorado, on the automation of furrow irrigation systems; and O. W. Howe at the Northern Plains Branch, ARS, Grand Junction, Colorado, on design performance, and automation of surface irrigation.

Until recently, most of the automation research dealt almost exclusively with surface irrigation systems because of the lack of proper and efficient equipment for automation by other methods. One of the great strides in on-farm irrigation automation has been the development of self-propelled sprinkler units capable of applying a desired amount of water at application rates compatible with the soil intake rates. With properly designed self-propelled sprinkler or solid set units, automation of irrigation systems can produce high on-farm irrigation efficiencies.

CHAPTER III

SYSTEMS MODEL AND CHARACTERISTICS

The General Model

As pointed out in the previous chapter, the ultimate irrigation system will be one that is totally automated using sensors or other devices as a controlling input to regulate the water distribution system which provides the crops with the proper amount of water when and where the plants need it. The result of such a system will be more efficient crop production, improved crop yield, and higher water use efficiency.

One of the principal objectives of this thesis is to present a proposed model of such a system designed primarily for use in the agricultural environment found in humid areas like the state of Georgia. The basic design model of an automated closed-loop irrigation system might be considered as a generalized feedback control system (Figure 2). To better the proposed system, it would be beneficial to discuss the key components necessary for the system to operate efficiently. Remote sensing by moisture sensing devices or by devices that sense the need for water directly in plants is probably the key factor in the system. Sensors are available that can detect the changes in soil moisture with sufficient confidence to aid in controlling irrigation systems. However, the sensing methods available to determine the moisture status of the soil lack efficiency such that no single device can find widespread acceptance as the ultimate sensor (18). Two of the devices that can be used very successfully in Georgia are the tensiometer and the electrical resistance block.

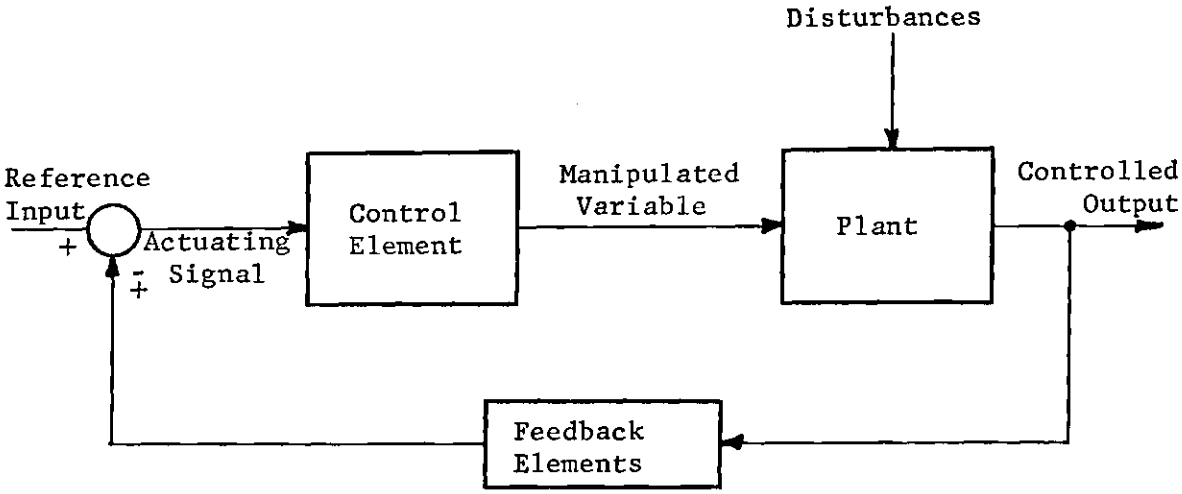

Figure 2. A General Feedback Control System

Sensing Devices

The tensiometer is a measuring device consisting of a sealed, water-filled tube equipped with a vacuum gauge on the upper end and a porous ceramic tip on the lower end (Figure 3).

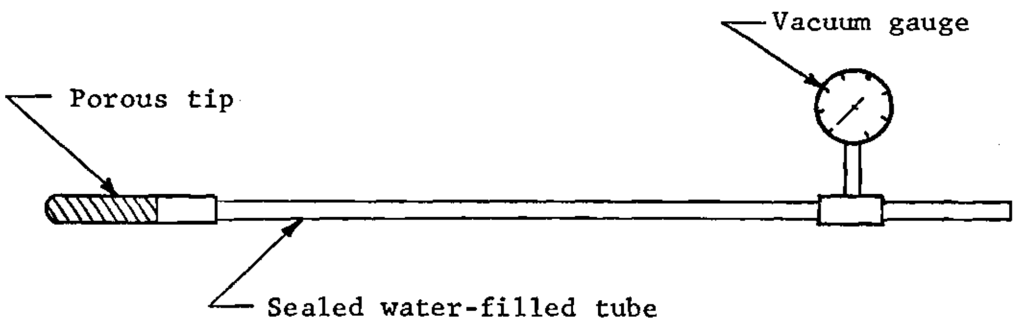

Figure 3. A Tensiometric Sensing Device

The suction produced as the plant roots remove water from the soil draws water from the sealed water-filled tube through the porpous tip and the change registers a vacuum. The drier the soil the higher the reading while the wetter the soil the lower the reading (Figure 4). Since this device measures actual moisture condition of the soil, it is an excellent tool for a control sensor (19). Tensiometers are relatively inexpensive, easy to construct, calibrate, and install, and are readily adaptable as a control link in a closed-loop system.

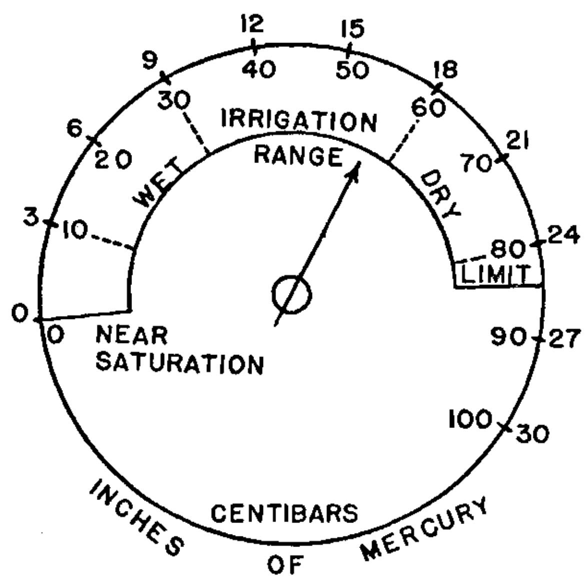

Figure 4. A Tensiometer Vacuum Gauge Dial

The other device used in detecting soil moisture is the electrical resistance block system (Figure 5). This system uses small gypsum blocks and a portable resistance meter to measure the moisture content of the soil. The blocks are made generally by casting gypsum around a pair of stainless steel wires or grids which are attached to meter lead-in wires. After the blocks are placed in the soil, the moisture content of the gypsum tends to equal the soil moisture content. As the electrical resistance of the wires in the gypsum varies with the moisture content, the measurement of the electrical resistance by the meter provides a good indication of the soil moisture content (20). These blocks have a number of advantages for "in situ" measurement. They are also relatively inexpensive, easy to install, and lend themselves to automation.

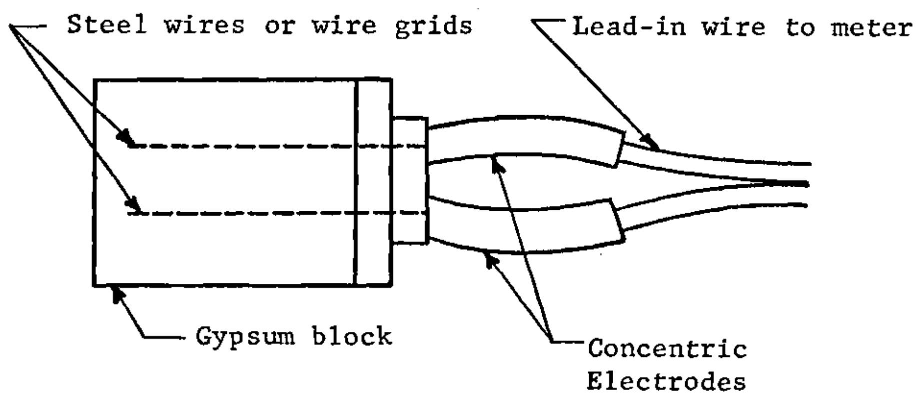

Figure 5. The Electrical Resistance Block

The tensiometer is most accurate in the wet range and the electrical resistance block is most accurate in the dry range of soil water content. It is conceivable to use the block to turn on a system as the soil reaches a given level of dryness and a tensiometer to turn the system off as the soil reaches the field capacity of wetness. Placement of either of these devices is based on stations that set up a zone of moisture control in the soil.

Location of the Devices

A station consists of two or more devices installed at various depths in the soil and usually in the crop row. Depth of the sensing devices in the soil is determined by the active root zone of the crop (Figure 6). This zone is dependent upon the crop, stage of growth, and depth of soil. A guide for installation is given in Table 1. The depths recommended may be modified if conditions in the root zone warrant it.

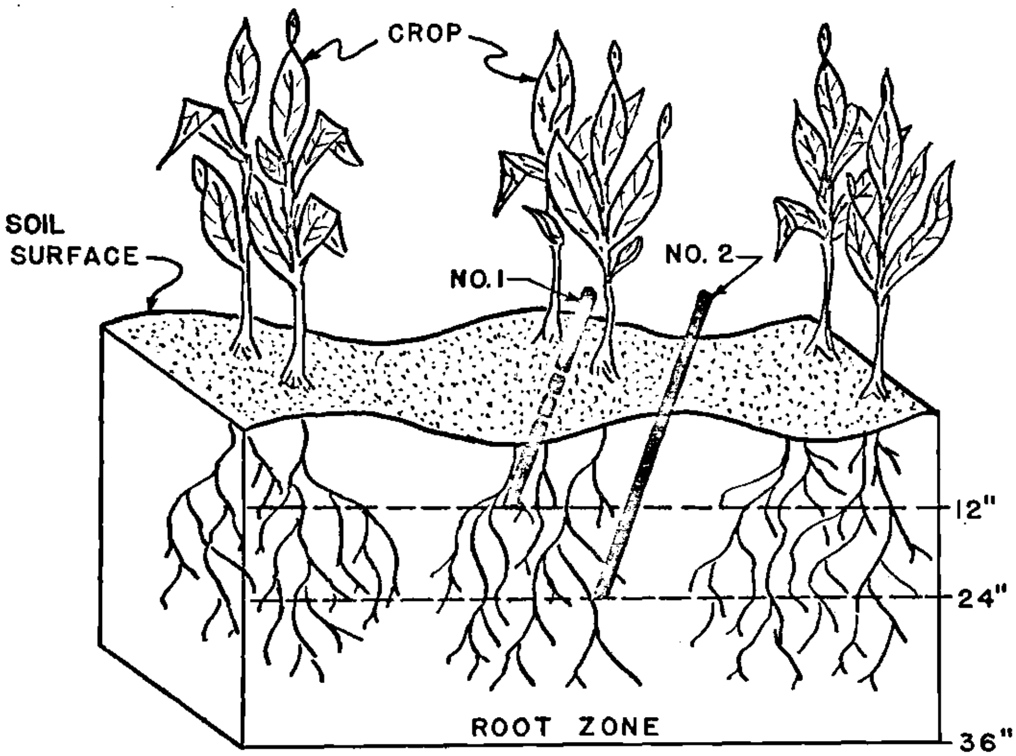

Figure 6. Location of Sensing Devices

Table 1. Recommended Depth of Setting or Placing Sensors

Soil Depth or Active Root Zone (inches)	Shallow Device #1	Deep Device #2
18"	8"	12"
24"	12"	18"
36"	12"	24"
48" or more	18"	36"

Irrigation Distribution Systems

The next component of interest is the irrigation distribution system. As mentioned in Chapter II, the sprinkler type of irrigation system is by far the most useful and adaptable system for use on the crops and soils found in Georgia. The main reason is because sprinkler irrigation is especially well adapted to rolling land or where the soil is shallow or too porous for surface methods, and where the water supply is limited. Flexible joints of the quick-coupling pipe make the system easy to install over fairly rough land. One of the important features of the sprinkler system is that the sprinkling rates can be adjusted to meet the soil intake rate which precludes the wasting of water and the erosion of soil. Also, since the correct amount of water needed at each irrigation can be obtained, control of this proper amount of water per application will prevent either over or under watering of the land (21). Today's agriculture uses sprinkler irrigation on 20 percent of the irrigated areas in the U.S. As water supplies become more critical, this is expected to increase to at least 80 percent (22).

The design of any sprinkler irrigation system is affected by many farm features such as the location of the water supply, the size and shape of the field, the soil characteristics, and to a lesser extent, the topography. The material effect on the system by certain soil, plant, and water relationships must be studied and analyzed before the proper system is installed. The rate at which water is drawn from the soil depends on the transpiration of water by the plants, and the evaporation of water from the plant and soil surfaces. Generally, the maximum rate of moisture use occurs, when the temperature is highest, daylight hours are long, humidity is low, wind movement is strong, and the plant is growing rapidly with a good root system. The root zone depth significantly affects the amount of water withdrawn from the soil.

Some of the sprinkler distribution systems suggested for best use in Georgia and which can be automated in a closed-loop system are the solid set, the center pivot, the side-roll, and the traveling gun systems. The solid set system is a system with portable lateral pipes spaced at regular intervals across the field so that the entire field receives a uniform application of water without moving any pipe. A center pivot irrigation system has the sprinkler laterals mechanized by anchoring one end of the lateral pipeline and connecting it to the water supply at the center of the irrigated area (Figure 7). The lateral is then continuously moved in a circle around the center pivot point. System propulsion is provided by hydraulic water drive, hydraulic oil drive, electric drive, or pneumatic drive. Such systems are best adapted for use on soils with a high intake rate, and a fairly uniform topography.

The side-roll continuous wheel move system is simply a lateral line of sprinklers mounted on a series of wheels (Figure 8). The system is mechanically moved by an engine mounted at the center of the line, or by an outside power source at the lateral end. The continuous travel is made possible by a flexible hose that can be dragged by the unit. The sprinklers remain in operation as the entire line traverses the field. The final system to be considered is the traveling sprinkler. It is basically a single large sprinkler mounted on a portable wheeled unit as illustrated in Figure 9. The unit is initially positioned at one end of a travel path, connected to a flexible water supply line. It is then self-

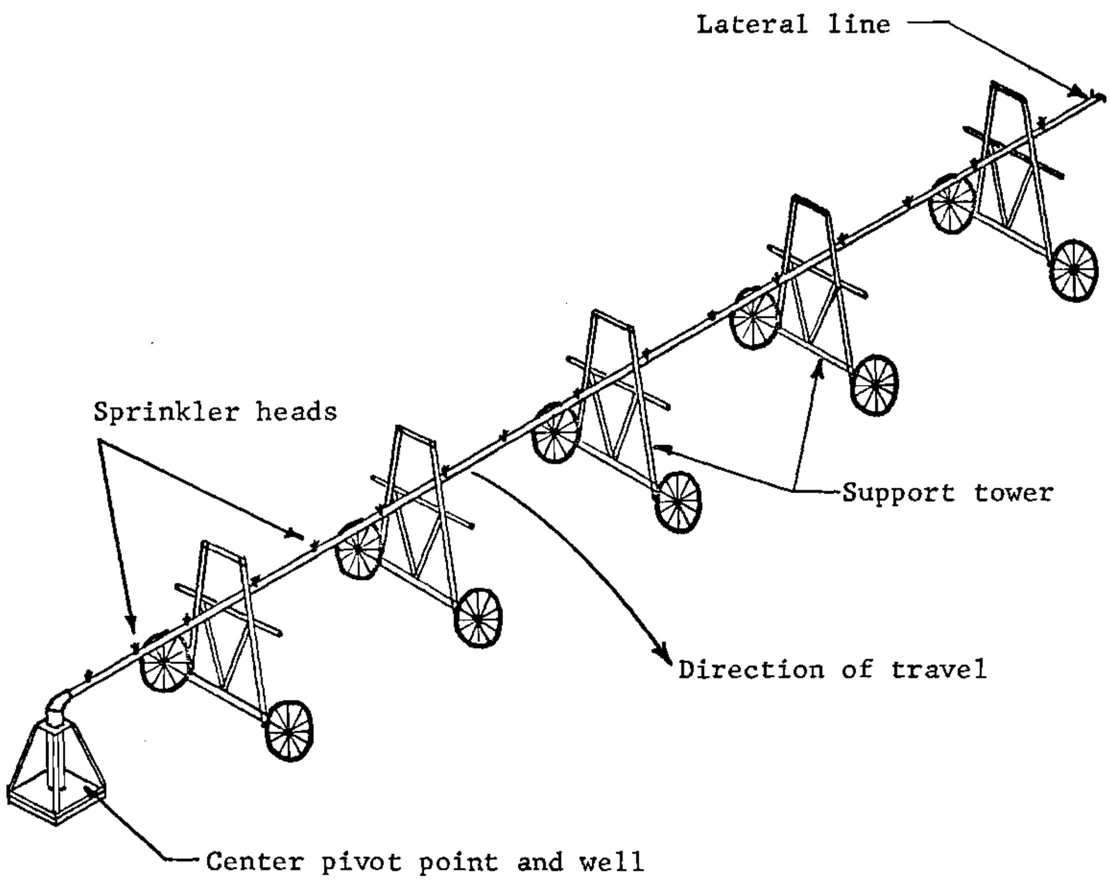

Figure 7. The Center Pivot System

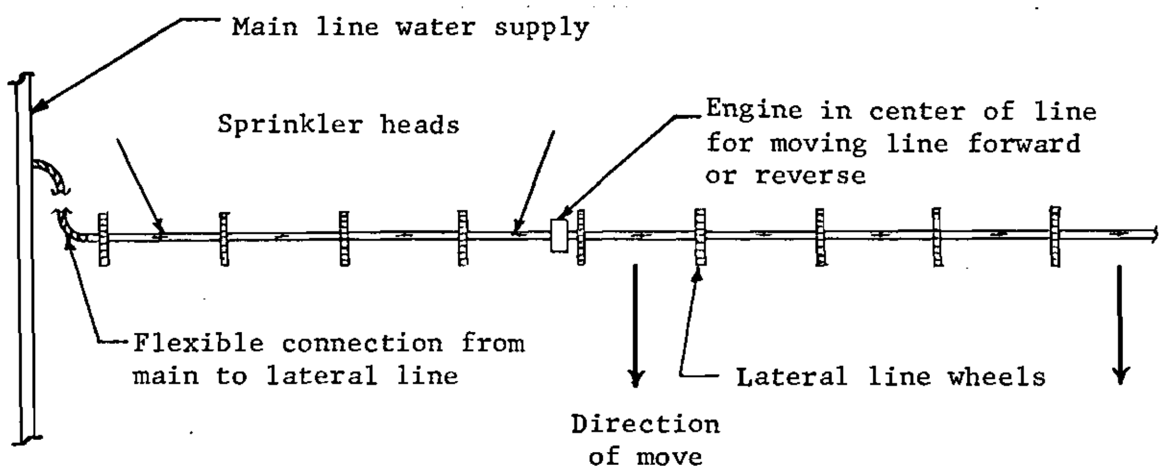

Figure 8. The Side-roll Wheel Move System

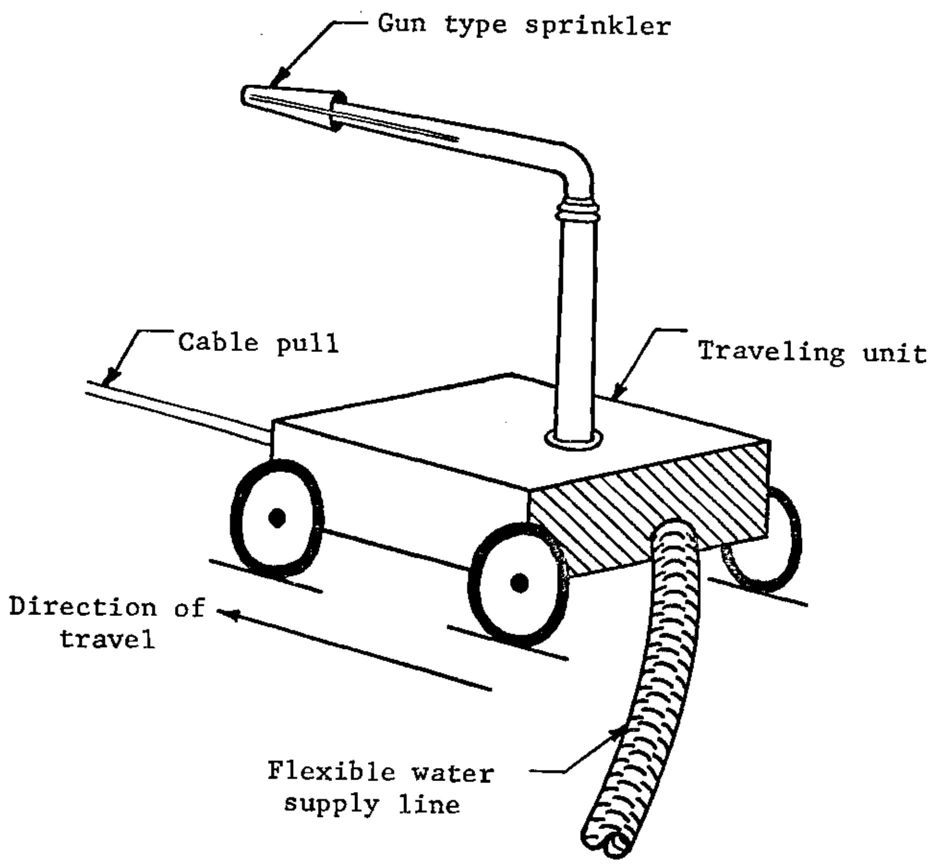

Figure 9. The Traveling Sprinkler

propelled to the other end of the travel path. Depending on the size of the field and the number of units, repositioning on an adjacent travel path may be unnecessary.

The continuous movement of all the self-propelled systems contributes to a good, uniform application of water to the soil. In addition, it maximizes the number of hours that the system can be used while reducing, or even eliminating, downtime for making intermediate moves.

The Controller

The final component of the closed-loop irrigation system to be considered is the main element of the controlling mechanism. The component which will control the entire system will conceivably be a small, digital computer available on a time-sharing basis, cooperative ownership, or individual purchase. The availability and wide range of computers which can handle the various requirements demanded in a closed-loop system preclude the need to describe their many advantages and characteristics. It is sufficient to say that a reliable automatic data processing digital computer that can handle the input and output signals is all that is needed to complete the basic system.

Final Selection

Each farmer selecting the various components of a system has his own set of circumstances and economic conditions to consider in building the system which will best satisfy his own requirements. The selection and installation of a closed-loop system are an economic compromise of these individual conditions, and no two systems may ever be exactly alike.

CHAPTER IV

METHOD OF PROCEDURE

The objective of an efficient irrigation system, particularly a closed-loop system, is to keep the soil moisture content between the "field capacity" and the "wilting point." The general model of a system designed to meet this objective was developed and presented in the preceding chapter. This system is of such a complex nature that description by a mathematical model is not considered to be feasible. Therefore, the systems analysis technique chosen to prepare a quantitative model of the system is simulation.

Systems Concept

Prior to simulating the overall system it was necessary to develop a systems concept of the conditions to be analyzed. The first condition encompasses the maintenance of moisture level input to the crop plants when the moisture input to the field moisture subsystem is rainfall alone (Figure 10). Deep percolation, surface runoff, evaporation, and transpiration are considered as disturbances to the system and are factors to be treated in each of the three conditions simulated. The effects of these variables can be controlled to a limited degree and will be subjected to controls under the appropriate conditions.

The second condition considers the use of a manual irrigation system as a regulator between the field moisture subsystem and the controller. The controller represents the guides or tables for irrigation scheduling

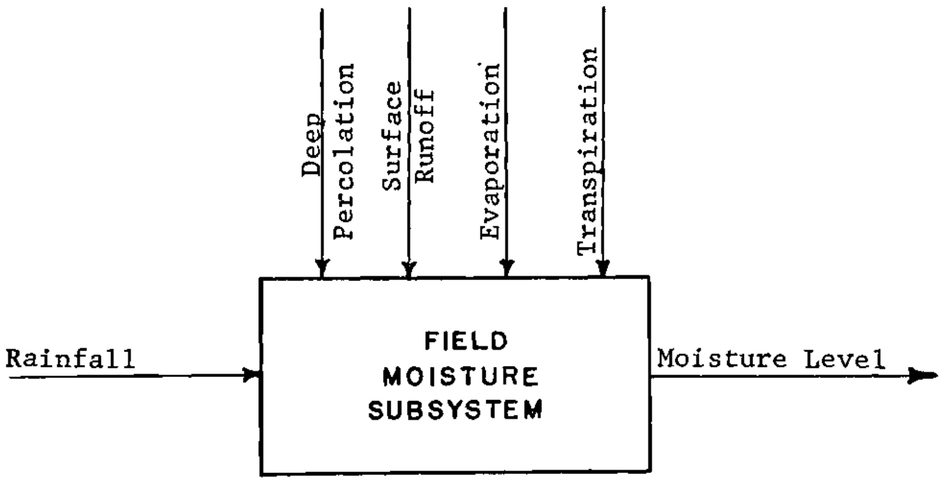

Figure 10. The Condition One System (Open)

available to the farmer and the reference input of the desired moisture level or wilting point for a given crop and root zone depth (Figure 11). Such a system is considered to be an open end system because no feedback is involved with the maintenance of a given moisture level.

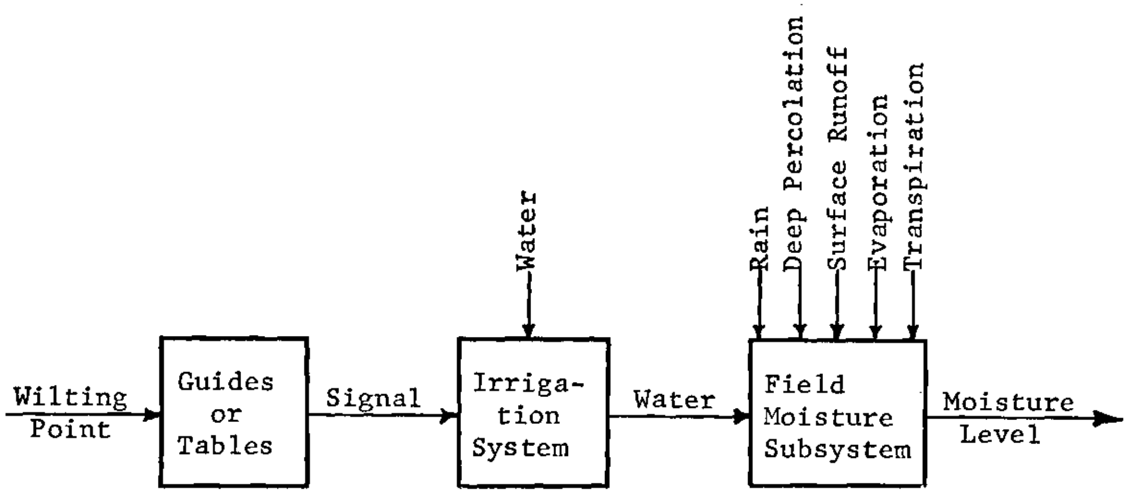

Figure 11. The Condition Two System (Open)

The final condition to be simulated is the condition representing the closed-loop irrigation system. Conceptually the irrigation system is considered to be a regulator subjected to automation and controlled by a computer. The computer is the principal element in the controller and is capable of analyzing the feedback data in relation to the reference input and other decision criteria. It actuates the irrigation system when necessary to maintain the water flow to the field moisture subsystem such that the moisture level input to the field is more efficiently controlled. The closed-loop system (Figure 12) allows a precipitation forecast to be made which enables the controller to better analyze the decision criteria.

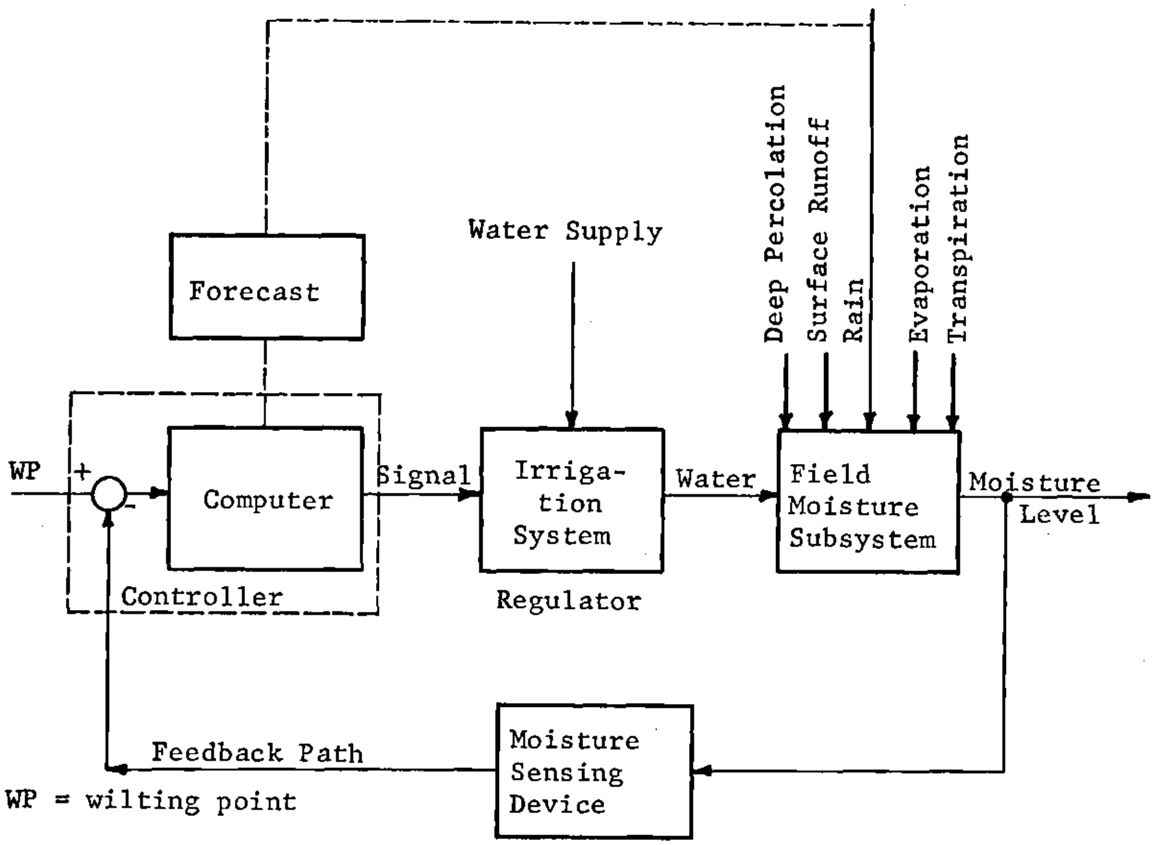

Figure 12. The Condition Three System (Closed-loop)

System Simulation Factors

In preparing the simulation model and developing the FORTRAN program for simulation, it was necessary to determine what factors should be considered and quantified. It was found that the soil moisture relationship for a known plant root zone of a selected soil and crop has an evolutionary cycle relating the depletion and replenishment of water for a given field. Figure 13 illustrates the cycle of soil moisture depletion by evapotranspiration and replenishment by irrigation or rainfall. The characteristics derived from this relationship and the above objective are that timing and the amount of water applied are the two most important factors affecting irrigation efficiency (23). Other variables in the model were selected because of their quantifiable nature in relation to an efficient irrigation system. Measurements were made of the water delivered to the fields, precipitation, surface runoff, length of growing season, evapotranspiration rates, and the critical periods for water.

By simulating the growth of a particular crop under conditions of rainfall without supplemental irrigation, a comparison can be made with the results of crop production when subjected to either manual irrigation or the closed-loop irrigation procedure. The decision was made to select several crops from those grown in Georgia and to simulate their growth under these three separate conditions. Figure 14 contains the general flow diagram for the simulation algorithm.

It was decided that the three conditions would be simulated for a six year period which is considered to be sufficient to obtain representative results for the conditions. Since data were available for a six year period concerning the actual rainfall, probability of rain, and the expected

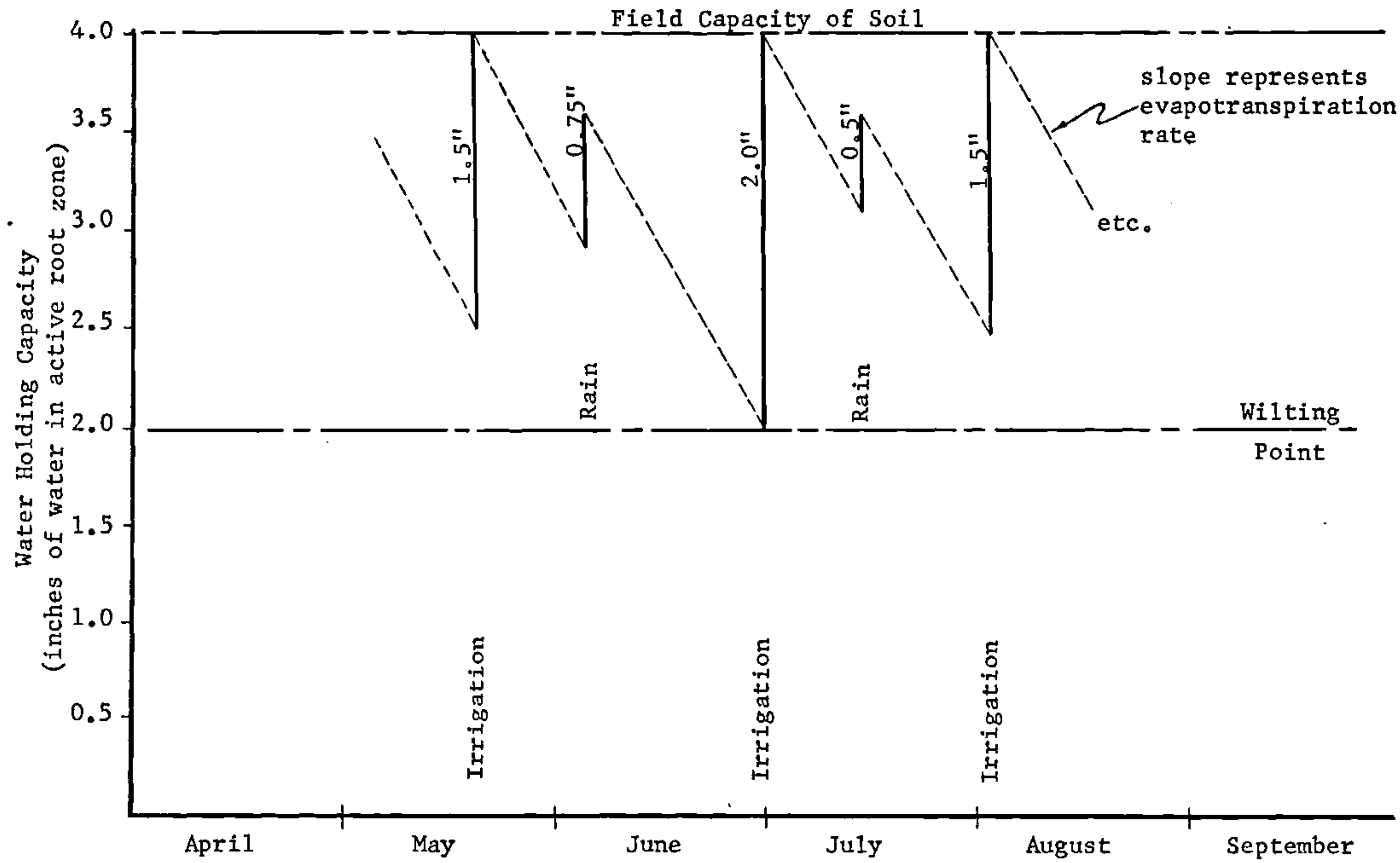

Figure 13. Diagram of Moisture Depletion and Replenishment by Rainfall and Irrigation

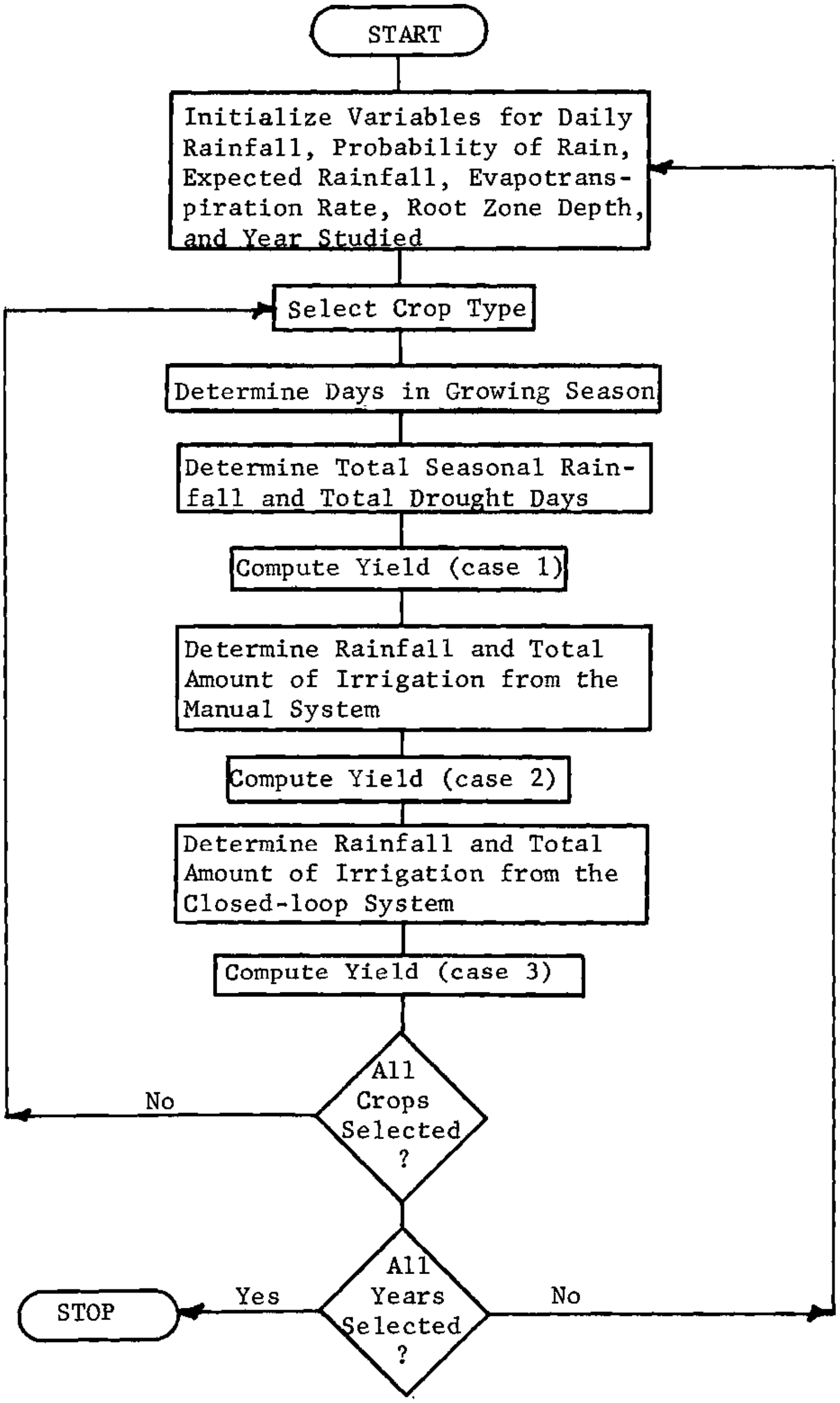

Figure 14. A Generalized Flow Diagram of the Simulation Algorithm

rainfall for each of the areas from which the test data were taken, the empirically distributed data for each year chosen serve as a base for which the model variables can be subjected. The years 1962, 1964, 1966, 1967, 1968, and 1969 were selected because the data within each year cover the majority of factors affecting crop growth such as droughts, long wet periods, heavy rainfall days, and varying seasonal rainfall quantity.

Evaporation and transpiration are considered the major means of water disposal from the field. Separating these pathways into each of the factors is very difficult and the subject of continued research. Farmers and researchers alike refer to this use of water as evapotranspiration. This factor is considered a key to controlling soil water content and for irrigation scheduling. The variability of this factor is one of the key elements represented in the simulation of the closed-loop system.

In addition, the simulation program is designed to allow for the computation of the amount of excess water applied resulting from either deep percolation or surface runoff. Inclusion of this variable in determining crop yield is not attempted because the assumption is made that all water applied to the field is effective in determining the crop yield. Research work is being conducted to actually determine how much water applied is directly related to crop yield. However, the results are not available for contribution to this thesis. The total quantity of water loss is considered in the variable called runoff in the program and is computed for each condition simulated. Since the data will not contribute to the overall results, further breakdown is not necessary.

Potential Water Distribution

In developing the simulation it was also necessary to analyze the potential water distribution pattern which would affect the crop growth. The distribution pattern includes the application of water to and removal of water from the soil (Figure 15). There are only two ways in which the soil can obtain water. One is by natural rainfall and the other is by the process of irrigation. Depending on the region in which the soil is located, the amount of water delivered to the field by irrigation may be the primary source of water or the supplemental source.

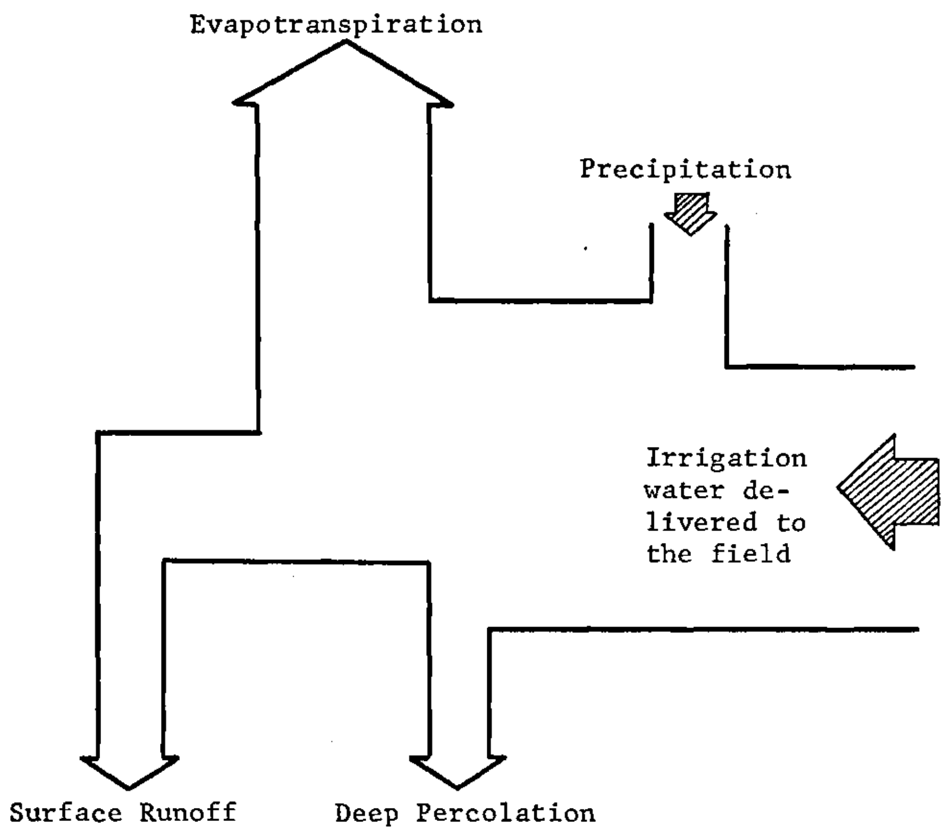

Figure 15. Potential Disposition of Water on Fields

Magnitude of Evapotranspiration

There has been a tremendous amount of study and research conducted related to the determination of the evapotranspiration rates for given crops, soils, climatic regions, and other factors. The results have generally recognized the fact that there are wide variances in rates from crop to crop, day to day, and even hour by hour from the same crop. Evapotranspiration rates are affected by a conglomerate of effects including temperature, humidity, soil texture, wind, stage of crop growth, and amount of vegetation present. Use of these rates by farmers generally is limited to a constant rate which has been determined by research to be fairly representative of the long term loss due to evapotranspiration. While this constant rate is better for the farmer who is irrigating his crop than not allowing for such a loss rate, it fails to achieve the needed efficiency desired for a well-managed irrigation system.

As the cost of facilities for collection, storage, and delivery of water increases, it will become necessary to design and operate an irrigation system with a much greater efficiency than previously thought possible. The future irrigation system must be designed to include the probability of peak and low rates associated with evapotranspiration.
The most recent work in developing a probability distribution for evapotranspiration has been done by J. L. McGuinness and Leslie H. Parmele (24).

The estimated frequency distribution used in deriving the probability distribution was obtained from meteorological data and from observed values for the weighing lysimeters at the North Appalachian Experimental Watershed. The results of their work indicated that all the data sets from the tests were of a log-normal distribution. After studying their test procedures and analyzing the outcome of their research, the assumption was made that such a distribution could be considered valid as the probability distribution of evapotranspiration for the crops chosen.

Conditions Under Simulation

Condition One

In this phase of the program, the daily soil moisture level is determined by an equation which relates the level from the previous day, the evapotranspiration rate for the specific crop studied, and the daily rainfall level. In developing this equation, the assumption was made that the soil moisture level for the day prior to the simulation period, that is, days of the growing season, would be 50 percent of the soil moisture holding capacity. This would provide a firm basis for starting the simulation and the assumption is justified because of the great variance in moisture level and a lack of empirical data about soil moisture conditions prior to a crop being planted.

The moisture level for the first day in the growing season is determined from the following equation:

$$DSM(1) = SOILM(I) + DRF(1) - EVR(I) \tag{1}$$

where DSM(1) = daily soil moisture level in inches for the first day of the growing season

SOILM(I) = soil moisture holding capacity for the I^{th} crop

DRF(1) = daily rainfall in inches on the first day

EVR(I) = the constant evapotranspiration rate for the I^{th} crop.

All the variables used in this and subsequent calculations related to determining soil moisture levels are in inches per day. Each subsequent calculation of the moisture level is based on the previous day's level. For example, this equation is:

$$DSM(J) = DSM(J-1) + DRF(J) - EVR(I) \quad (2)$$

where DSM(J) = daily soil moisture level for the J^{th} day of the growing season

DRF(J) = daily rainfall for the J^{th} day.

The use of a constant rate for evapotranspiration in this equation is justifiable because the nature of the variance in the rate under conditions of natural rainfall alone is not quantifiable by the average farmer. Additionally, any consideration of the rate in determining the daily soil moisture level as it affects the yield is limited to the mean rate. As the simulation of this condition progresses, the rainfall affecting the crop is accumulated to be used in determining the yield from a production function. Conceivably crops are subjected to the conditions of drought during the growing season. Determination of the drought days is made when the daily soil moisture level is computed to be less than zero for any 24-hour period. When this condition occurs it is treated as one drought-day and is accumulated for use in determining the crop yield. Each of these variables is placed in the production function and computation is made of the yield in relation to these variables. Since this condition does not consider the effects of any supplemental irrigation, the irrigation variable in the production function is of zero value.

Condition Two

The simulation of this condition subjects the crop considered in the above case to the same factors with the exception that the crop will be affected by an added quantity of water delivered by a supplemental, manual irrigation system. The daily soil moisture level is again the basis for simulation. Computation of the level for the first day is determined as given in equation (1) except that a variable for quantity of water applied is added. Thus, equation (1) becomes:

$$DSM(1) = SOILM(I) + DRF(1) - EVR(I) + RGN \qquad (3)$$

where RGN = amount of water applied by irrigation.

Equation (2) is also changed as follows:

$$DSM(J) = DSM(J-1) + DRF(J) - EVR(I) + RGN \qquad (4)$$

For each crop selected, irrigation requirements have been formulated by the Cooperative Extension Service. Discussion of each of the individual crop characteristics is provided in a subsequent section of this chapter. However, in order to determine the amount of water that a farmer would apply to any one of these crops, the decision criteria were established in accordance with the guidelines set by the Extention Service. The recommended times for irrigation consider the critical stage of growth, the distribution of rainfall, the likelihood of drought, the soil type, crop type, and the evapotranspiration rate.

It was assumed in developing the decision criteria for this phase that a farmer with a manual irrigation system, growing the crops selected, and practicing good farm management, would subject himself to the same decision criteria for irrigation purposes. The amount to be applied at each irrigation is determined for the same conditions considered for the time to irrigate by using the guidelines provided by the Extension Service.

The program treats the crop used in Condition One to the characteristics of Condition Two for the same period of time. The quantity of rainfall applied under the first condition will be the same for the second and is not recomputed. The summation of the water applied by irrigation is kept current for each application as is the number of applications. At the end of the simulation of Condition Two, the variables of rainfall, irrigation, and drought days are considered in determining the crop yield.

If the crop is subjected to irrigation during the course of the simulation under Condition Two, it is assumed that the effect of drought on the crop has been minimized. Therefore, the variable for the drought-day in the production function is assumed to be zero, which allows for a negated effect on the crop from drought. This assumption is justified since, by using irrigation during the growing season, the farmer is attempting to minimize the effects of drought to insignificance.

Computation is made of the crop yield by the production function in relation to the values of the variables determined from the simulation of Condition Two.

Condition Three

Simulation of crop growth for this condition subjects the crop to the characteristics of rainfall when supplemented by irrigation controlled by a closed-loop system. The determination of the daily soil moisture level is similar to Condition Two with the exception that the evapotranspiration rate is not treated as a constant. A process generator which allows the evapotranspiration rate for each day to vary in accordance with a log-normal distribution is included in the simulation routine. The purpose is to simulate the actual variance in the rate which occurs in the natural growth cycle of the crop. The first day level is then computed from the following equation:

$$DSM(1) = SOILM(I) + DRF(1) + RGN - ETR \tag{5}$$

where ETR = the computed evapotranspiration rate having a log-normal distribution.

Subsequent calculations are then made using this equation:

$$DSM(J) = DSM(J-1) + DRF(J) + RGN - ETR \tag{6}$$

The determination of the rainfall variable for this condition is identical to the previous condition. Since this condition is representative of a closed-loop system the simulation is directed toward meeting the objective given earlier of an efficient system in relation to the key factors of timing and the amount of water applied. Consideration is made first of the timing of the irrigation. As the soil moisture level declines by crop use, a check is made to determine if the level is below 50 percent of the available moisture specified for the crop and its root zone. If the check is negative, then no irrigation is permitted. If the result is positive, further checks are mandatory before irrigation is permitted. In actual practice it would not be considered an economical use of the system as well as good water management to irrigate one day only to be followed by an effective rainfall the next. The purpose of this system is to supplement the natural rainfall, not to preempt it.

Criteria are then set to allow the system to check the probability of rain for the following day and to determine whether waiting for the rain will be worth the risk. Since the moisture level is just below the 50 percent level, waiting one day for rain dependent on the probability of its occurrence would not be considered detrimental to the crop. Actual probability figures taken from National Weather Service records for each day of each year simulated have been included in the base data for the computer program. In establishing criteria for the probability of rain, it is useful to consider the expected quantity of rain for the day. It is conceivable that the probability of rain on a given day may be very high but the expected amount of rain could be very low. Under such a condition the farmer may feel the risk too great and will allow the irrigation to proceed. For the purpose of this simulation the assumption is made that the decision criteria for irrigation will include the probability of rain and the expected amount of rainfall for each day simulated.

The decision levels selected for use in this program are purely arbitrary in nature. Risks on the part of the farmer are individual considerations and no two farmers may establish the same criteria. In the program, allowance has been made to check the probability of rain and expected outcome under two separate decision levels. First is the condition of high probability of rain and an expected outcome of rain which is at least that of the constant evapotranspiration rate. The other condition allows a lower probability of rain but the expected rainfall must be greater than .75 inch. Should either of these conditions fail to be satisfied, then irrigation will take place.

Now that timing of the irrigation has been effected, determination is made of the amount of water to apply. The irrigation system will apply a quantity which is equal to the difference between the field capacity and the soil moisture level on the day of determination. However, since irrigation is scheduled to begin on the day following determination, the possibility of actual rainfall is considered. This in effect allows the simulation to represent the stoppage of the irrigation system when rain is encountered. If the field was being irrigated and rain begins to fall, the system would shut down on command of the controller and allow the natural precipitation to take over. The moisture sensing devices would continue to relay the moisture level of the field to the control element. If insufficient rain did fall, the device would sense the inadequate moisture level and the controller could direct the system to begin irrigating again.

At the end of the Condition Three Simulation the variables of rainfall and irrigation quantities are placed in the production function equation to produce the crop yield for that period.

The Production Function

Crop yield is the response by which a comparative analysis is made between each of the simulated conditions. Therefore, it was necessary to develop a function which would relate crop yield to the quantity of water delivered to the field or the lack of water in the field. To define this function, a methodology developed by Dan Yaron, Harvard Water Program, was used (25). His approach resulted from an empirical analysis of the demand for water by agriculture. The basic thesis in developing the criterion for a crop production function was that, in the economic analysis of the complex problem of water resource in agriculture, irrigation water must be treated as any other production factor affecting the process of crop production.

The overall outcome of the research by Yaron resulted from a normative and positive study at the farm level where a detailed analysis was made of the microstructure of the demand for water by crops. The study was based on one of the major theories regarding water-soil-plant relationships (26). The theory contends that plant response to soil moisture is varied and that a change in the moisture regime during the plant growth stage results in a corresponding change in crop yield. One of the major problems associated with an empirical estimation of a production function based on this thesis is the specification and choice of the independent variables such that the dependent variable is crop yield per unit of land. In satisfying this approach, it was necessary to relate the yield to the fundamental variables affecting the crop and which were operationally meaningful. Estimates from Yaron's research suggest that the curves fitted for a given crop in the same location but for different years have the tendency to run parallel to each other. The key observation made from his study led to the formulation of the hypothesis that, under conditions at one and the same location, the marginal crop yield is a function only of the quantity of water applied considering other irrigation variables equal (27). Accepting this hypothesis resulted in the following general specification for the crop production function:

$$Y = F(X_1, X_2, X_3)$$

where Y = crop yield per land unit

X_1 = amount of rainfall in inches

X_2 = number of drought days

X_3 = irrigation water applied in inches.

A production function was developed for each of four basic crops grown in Georgia selected for simulation of crop growth with varying demands for water and individual conditions for irrigation. The crops chosen were tomatoes, corn, cotton, and tobacco. They represent crops of high economic value and are grown in such quantity that irrigation data are available to determine the crop production function. In addition, crops with high income-per-acre value are the most profitable to irrigate. For each of the individual crops, a least squares estimate of Y as a function of X was determined, All data concerning rainfall, drought, and irrigation water applied used in deriving the production function were obtained from test results for each of these crops. These test data and the resulting production functions are given in Appendix II. The regression equation representing the production function is defined as follows:

$$\hat{Y} = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + B_{11}X_1^2 + B_{22}X_2^2 + B_{33}X_3^2 \quad (7)$$
$$+ B_{12}X_1X_2 + B_{13}X_1X_3$$

The values of X_i for each crop and test site were subjected to a multiple regression analysis in the form of a program written in FORTRAN for a UNIVAC 1108 computer. The results of the analysis on the crop data provided the regression coefficients for the B values in equation (7).

Crop Considerations

Since the amount of water applied to crops can, at times and in some places, be controlled or altered, then the magnitude of crop yield can be influenced. Increasing the supply will increase yields provided another factor is not more limiting and the application is provided at a time coincident with the need of the plants (28). Time of water application in agricultural irrigation is of primary economic importance because the contribution that water makes toward increases in crop yield varies with the stage of plant growth. This is exemplified in the production of crops for seed. Any water deficit during the reproductive stage can cause a greater grain yield reduction than a deficit at any other growth stage. These factors can be provided for by simulation of the growth period and by relating crop yield to water deficits during the life cycle or growing season of the crops considered.

An analysis of each crop selected included the length of growing season, critical periods of growth, evapotranspiration rate, and drought effects. This information was compiled by the Cooperative Extension Service to assist the farmer in managing his irrigation system. Figure 16 illustrates for cotton the relationship between these factors (29).

Cotton

Cotton makes good use of water within a wide range of limits. However, the plant makes better use of water during certain stages of growth

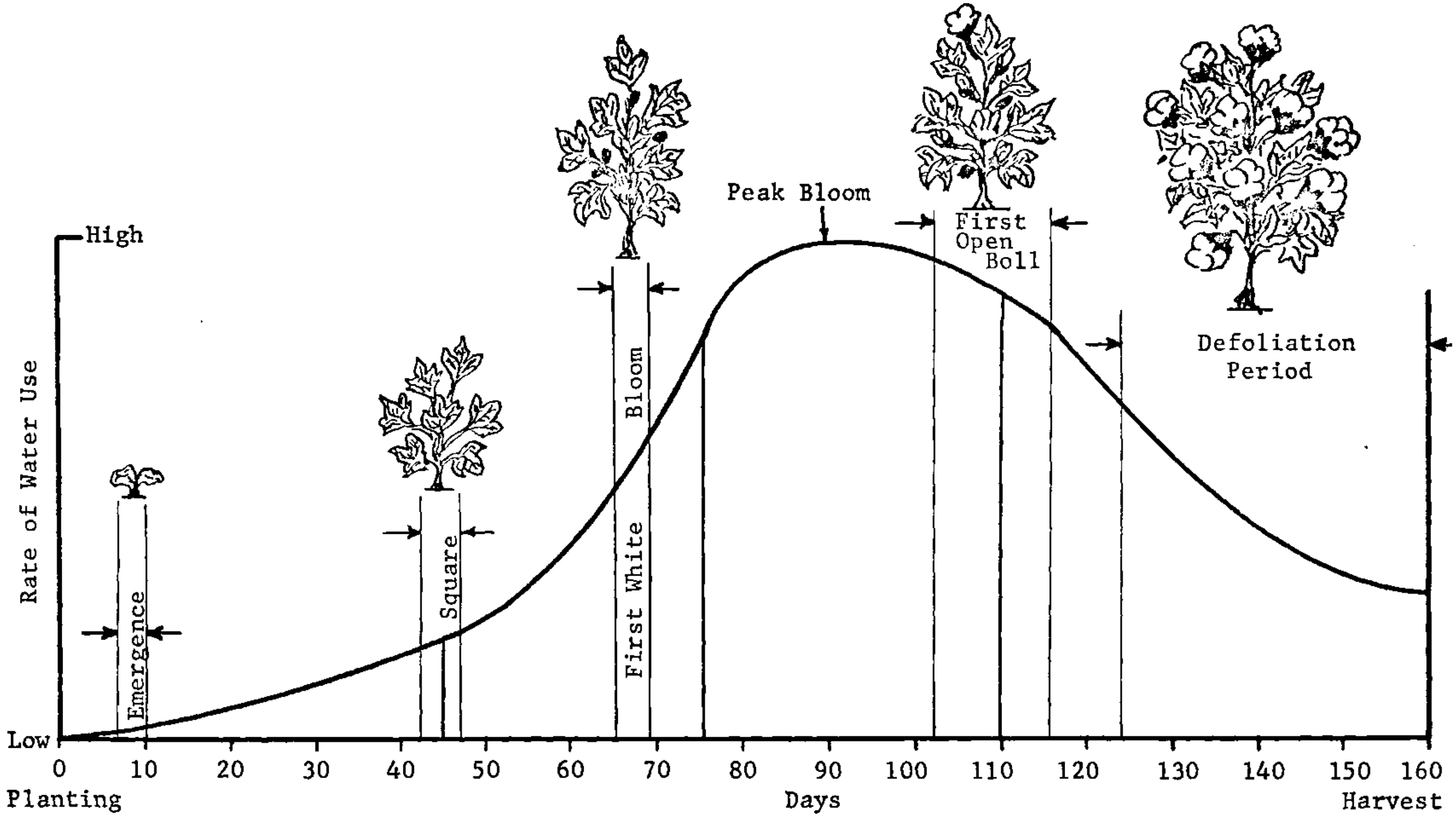

Figure 16. Moisture - Plant Growth Relationship for Cotton

than it does at other times. The plants will use approximately 0.21 inch of water per day. In the Coastal Plains, soil moisture can be kept above the 50 percent level by replacing 1.3 inches of water at each irrigation every six days. In the Piedmont region, the frequency of irrigation will be from 7 to 10 day intervals and from 1.4 to 2 inches of water should be applied per application.

During the first sixty days of growth of cotton, the demands for water are generally light but increase to a heavy demand when the squares start setting. This heavy need for water will usually continue through the fruiting period. In order to produce maximum yields it is important to get a good stand of cotton; therefore, it may also be necessary to irrigate at planting time (30).

Tomatoes

The evapotranspiration rate for tomatoes during the growing season is considered to be 0.21 inch of water per day. In the Coastal Plains soils generally hold about 1.2 inches of available moisture for crop growth. This means that every six days 1.2 inches of moisture should be replaced either by rainfall or supplemental irrigation. The frequency of moisture replacement in the Piedmont region is on 7 to 10 day intervals.

Tomatoes generally should be irrigated from the time they start producing fruit until the plants stop bearing. Soil moisture during this period should be kept high enough to preclude wilting in the plant or visible signs of the plants suffering from lack of water. Results from irrigation experiments with tomatoes indicate that the total number of tomatoes produced was the same with or without irrigation, but the size and quality were greatly improved where irrigation was used (31).

Corn

On the average the evapotranspiration of corn will be 0.23 inch of water per day and 1.6 inches of water should be applied about every six days. Corn needs water most from the time tasseling begins until the crop finishes silking. Irrigation after silking does not significantly affect crop yield enough to warrant the use of water and time to irrigate. Results of a four year test by the United States Department of Agriculture on the irrigation of corn indicate that the three best manual irrigation times over any other time considerations for manual irrigation were one application about ten days before tasseling, one at tasseling, and one at silking (32).

Tobacco

Irrigation of tobacco is profitable only if the application of water occurs at the proper time and in the proper amount. The demand for water by tobacco is generally limited primarily to supplemental irrigation during dry periods. Seasonal variations, different soil conditions, and cultural practices preclude a set schedule for applying water to tobacco. However, certain basic principles can be applied.

Tobacco has an evapotranspiration rate of 0.19 inch of water per day. Irrigation may begin in the plant bed or even before the seed are sown especially in extremely dry seasons. The lack of moisture in the plant bed, from the time the seed begins to germinate until the time the roots of the young seedlings are fairly developed, is considered to cause a greater loss of plants in Georgia than from all other causes combined.

Once the plants are well established, water may or may not be needed occasionally until transplanting occurs. If the soil is extremely dry, it is desirable to apply water. During the first few weeks after the plants are set, tobacco is benefited by a fairly dry soil, so little or no water should be applied during this period. However, if it is necessary to prevent scald or wilting, no more than 0.5 inch of water should be applied.

As the growing season progresses and the temperature remains high, the plant increases its demand for water. During this period irrigation is most necessary and profitable. Tobacco will require about one inch of water per week. After the tips fill out the requirement for water drops to about 0.50 to 0.75 inch per week. This amount of water is usually adequate to keep tobacco in a marketable condition and to prevent scald or severe wilting (33).

Precipitation Probability Forecast

The probability forecast actually encompasses two separate but related characteristics. In the actual operation of the closed-loop system, specifications may be made for allowing the moisture level to drop below the wilting point when the probability of rainfall and the expected rainfall are considered on a daily basis. The farmer can obtain precipitation probability forecasts from the National Weather Service which is designed to cover a 12-hour period. The forecast is intended to elaborate the basic prediction of rain and translates the difference between a remote chance and a virtually sure thing into numerical terms. Data used in the simulation were taken from official Weather Service records for the areas considered in the original crop tests.

The farmer must not be limited to the concern for the chance of rain but he must also look for the amount of expected rainfall on a given day. If the probability of rain is high and the expected rainfall is low or negligible, then he may decide to irrigate rather than subject the crop to a wilting condition. The farmer can use his experience to establish his criteria for a good probability of rain and a desired level of expected rainfall and then provide these decision criteria to the computer in the form of input data. The computer can then analyze the daily conditions and, when compared to the criteria for irrigation, can "decide" whether the irrigation system should be turned on. This action is one of the key benefits of the closed-loop system because it enables the farmer to get better and more efficient use from his system in relation to applying water when the crop needs the water. Additionally, it minimizes the chance of over-watering which contributes to crop yield reduction and/or soil damage.

CHAPTER V

RESULTS

The initial reaction to the overall results of the simulation of the three conditions of controlling moisture input to the crop production system is favorable. However, before any final conclusion may be drawn it is necessary to analyze the results for each crop under the separate moisture input systems studied.

Tomato Production

The six year production results for tomatoes grown under the influence of natural rainfall alone are presented in Table 2. The good yields in 1962 and 1969 probably resulted from the even rainfall distribution during the growing season. This would indicate that the proper timing of the application of water to the field is more critical in improving yields than the amount of water applied. The quantity of water applied in 1967 is much greater than either of these other two years, but the yield is less than half that of the other two yields. This low yield could be a direct result of the fact that, during the latter part of the growing season, rainfall in excess of nine inches fell on June 4, 1967. Heavy rainfall of this nature can drastically reduce the yield of tomatoes due to the damage to the fruit from excessive water.

Tables 3 and 4 contain the results for yields obtained by supplemental irrigation provided by the manual system and the closed-loop system, respectively. The comparatively low yields in 1967 can again be attributed to the excessive rainfall which occurred in June.

Table 2. Yield Results for Tomatoes--Condition One

Year	Yield (lbs/plot)	Rainfall (inches)	Drought Days	Runoff (inches)
1962	124.25	11.51	27	0.00
1964	73.48	17.82	29	5.32
1966	58.61	15.60	8	0.00
1967	53.47	22.54	26	8.09
1968	86.40	15.93	11	0.40
1969	122.86	11.77	29	0.17
	Six Year Yield Average 86.51			

Table 3. Yield Results for Tomatoes--Condition Two

Year	Yield (lbs/plot)	Rainfall (inches)	Irrigation (inches)	No.	Runoff (inches)
1962	138.75	11.51	6.5	5	0.00
1964	112.95	17.82	6.5	5	5.32
1966	116.23	15.60	3.9	3	0.96
1967	35.84	22.54	7.8	6	11.02
1968	118.40	15.93	3.9	3	1.33
1969	139.10	11.77	7.8	6	1.47
	Six Year Yield Average 110.21				

Table 4. Yield Results for Tomatoes--Condition Three

Year	Yield (lbs/plot)	Rainfall (inches)	Irrigation (inches)	No.	Runoff (inches)
1962	134.21	11.51	8.52	4	3.15
1964	127.78	17.82	6.92	4	7.27
1966	131.29	15.60	5.55	3	4.61
1967	94.50	22.54	5.76	3	11.43
1968	130.63	15.93	5.72	3	4.93
1969	141.16	11.77	10.04	5	5.15
	Six Year Yield Average	126.59			

It is evident from the yield results for tomatoes that there is validity in the conclusions drawn from the original test study that extra applications of water on tomatoes during the growing season over the suggested schedule provided by conservation guidelines have only limited benefit. The original test results indicated that the percent of usable tomatoes was not significantly affected by the level of moisture. Neither did the extra water affect the number of tomatoes produced. The significant effect from the increased moisture level was in the size and quality of the fruit. Since the price of tomatoes is related to the weight of the fruit, any increase in size will affect the weight of the tomato which will, in turn, increase the return on the investment. Figure 17 provides a comparative plot of the yields resulting from the three conditions.

Corn Production

Corn yields resulting from the effects of natural rainfall during

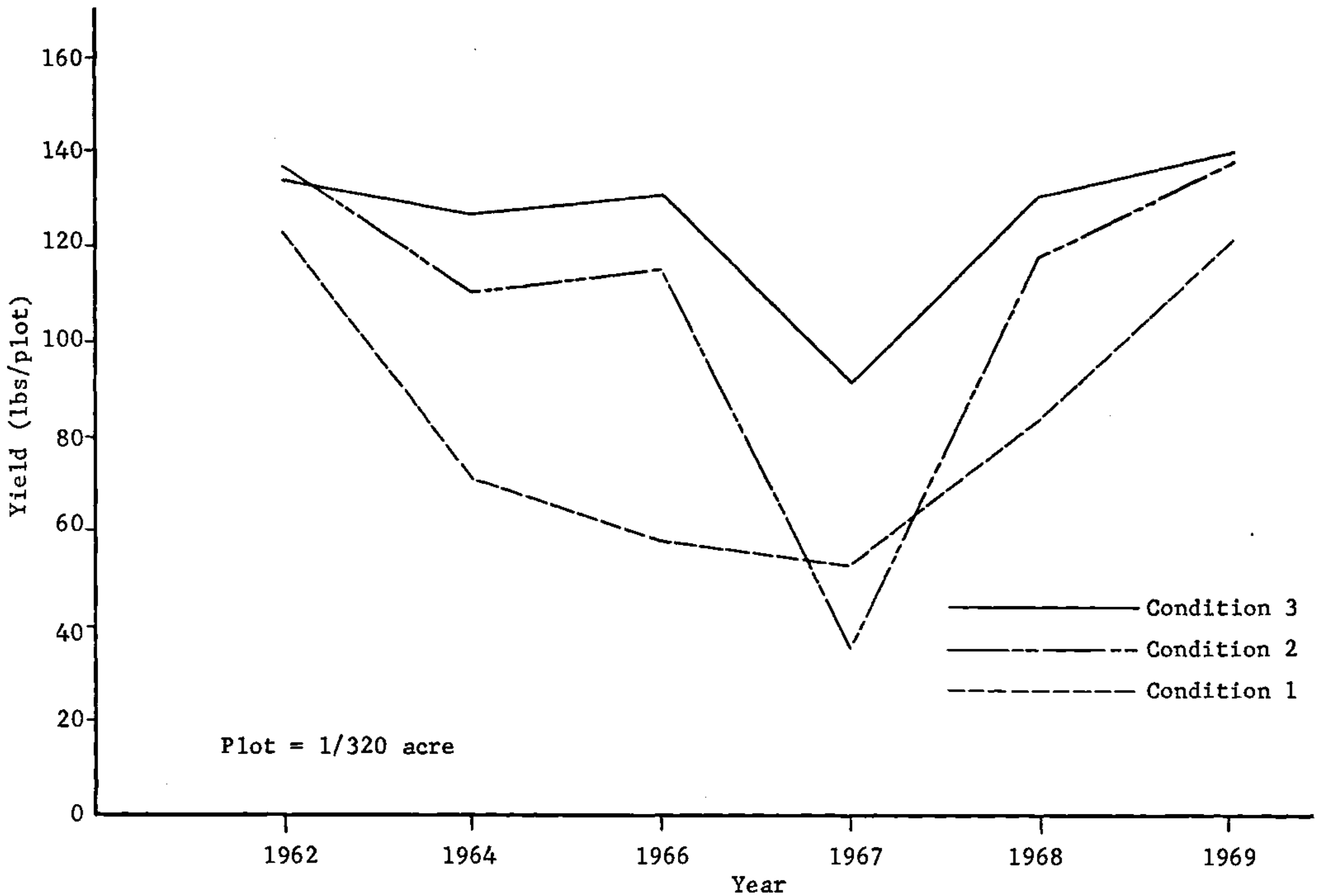

Figure 17. Tomato Production Results

the simulation period are presented in Table 5. An analysis of each of the yields in relation to the distribution of rainfall during the 120-day growing season indicates that timing the application of water is the key to improved crop yield. The variance in yields for 1962, 1964, and 1966 is small, but the rainfall variation is large. This would indicate that the occurrence of rain at the critical stages of growth enables the production to remain fairly stable.

Table 5. Yield Results for Corn--Condition One

Year	Yield (bu/acre)	Rainfall (inches)	Drought Days	Runoff (inches)
1962	65.04	15.71	53	0.12
1964	49.72	28.32	46	6.63
1966	62.26	17.56	50	1.21
1967	27.21	31.74	32	10.53
1968	36.38	24.43	29	3.63
1969	46.45	13.95	68	1.49
	Six Year Yield Average 47.84			

The corn yields resulting from supplemental irrigation show a significant increase with the greatest improvement occurring when rainfall is supplemented by a closed-loop irrigation system (see Tables 6 and 7). The estimated yields in Table 7 for 1964 and 1967 appear to be larger than one might expect. It is doubtful to assume that water has such a beneficial effect on corn production. In the author's opinion, the test data used to define the corn production function (see Table 16 and equation (9)) may have been biased to some degree in actually relating improved corn yield to the single moisture variable. Since the conditions under which the test was conducted are not available, no check can be made to either confirm or deny this supposition. If such a bias does exist, the results still show a significant improvement in yield when supplemental water is controlled by a closed-loop irrigation system (see Figure 18).

Table 6. Yield Results for Corn--Condition Two

Year	Yield (bu/acre)	Rainfall (inches)	Irrigation (inches)	No.	Runoff (inches)
1962	105.29	15.71	6.50	5	0.12
1964	107.44	28.32	4.90	4	6.63
1966	96.57	17.56	5.20	4	1.67
1967	83.87	31.74	3.90	3	10.53
1968	74.62	24.43	3.90	3	3.63
1969	102.67	13.95	6.50	5	1.49
	Six Year Yield Average 95.08				

Table 7. Yield Results for Corn--Condition Three

Year	Yield (bu/acre)	Rainfall (inches)	Irrigation (inches)	No.	Runoff (inches)
1962	152.29	15.71	11.96	9	4.24
1964	294.64	28.32	10.43	8	12.37
1966	179.03	17.56	12.06	10	5.78
1967	297.65	31.74	9.25	9	15.52
1968	215.98	24.43	9.57	8	9.62
1969	186.79	13.95	18.03	14	5.42
	Six Year Yield Average 221.06				

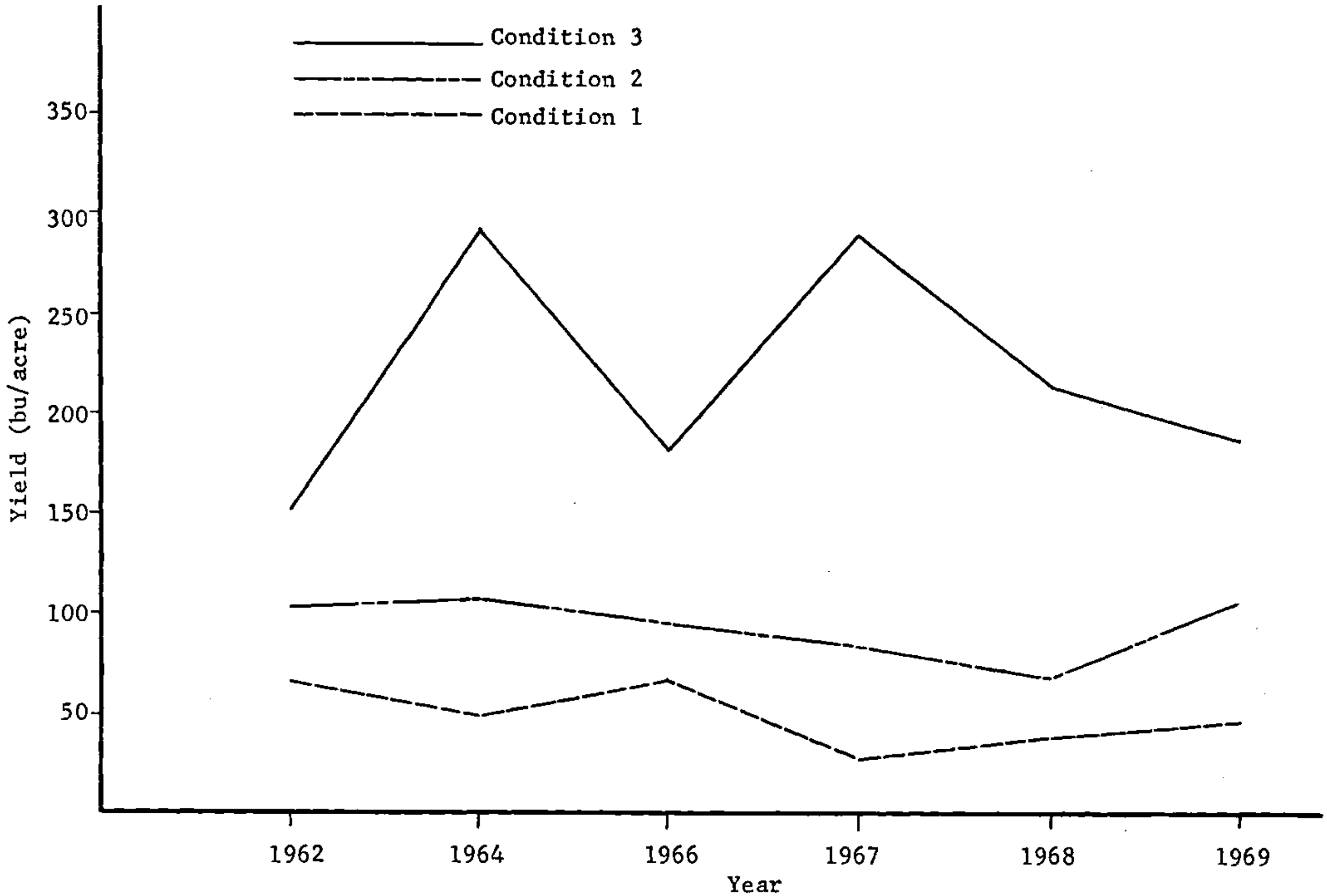

Figure 18. Corn Production Results

Cotton Production

For many years cotton was considered to be a drought resistant plant because some yield was always made, even during severe drought periods. This is exemplified by the consistent yield results under natural rainfall conditions as given in Table 8 with the exception of the yield for 1967. The same heavy rainfall discussed for tomatoes would also have had a detrimental effect on the cotton plant. Plausible causes for the reduction in cotton yield in 1967 probably were due to more vegetative growth causing late fruiting, more insect damage under wetter conditions, and greater leaching of plant nutrients from the excess rainfall.

The consistent yields for cotton when rainfall is supplemented by manual irrigation indicate that the factor of timing is an important consideration when manually scheduling irrigation (see Table 9). Another factor that may be considered is the need for cotton to be subjected to some periods of dryness. An analysis of the resulting yields for cotton when the closed-loop system is used seems to warrant such a consideration (see Table 10). It is felt that better decision criteria could be established for the closed-loop system so that the cotton would be subjected to some dry periods. In the author's opinion there would still be improved yields for the closed-loop system, but the year-to-year variability would be much less than is indicated in Table 10.

In view of the assumption made in Chapter IV that all water is effective, the crop response to the closed-loop irrigation system indicates a favorable improvement in yield over the response related to the manual irrigation system (see Figure 19). However, in order to achieve maximum benefits from either system on cotton production, it is also necessary to

Table 8. Yield Results for Cotton--Condition One

Year	Yield (lbs/acre)	Rainfall (inches)	Drought Days	Runoff (inches)
1962	1765.82	22.09	63	0.18
1964	1373.21	32.13	46	9.63
1966	1407.77	24.67	37	0.83
1967	387.37	34.66	19	10.29
1968	1201.09	28.50	34	3.54
1969	1786.45	22.95	68	1.92
	Six Year Yield Average 1320.28			

Table 9. Yield Results for Cotton--Condition Two

Year	Yield (lbs/acre)	Rainfall (inches)	Irrigation (inches)	No.	Runoff (inches)
1962	3356.72	22.09	9.1	7	0.21
1964	4773.76	32.13	6.5	5	10.17
1966	3611.91	24.67	6.5	5	1.07
1967	4542.76	34.66	5.2	4	12.30
1968	3629.75	28.50	5.2	4	4.98
1969	3517.34	22.95	10.4	8	1.92
	Six Year Yield Average 3905.37				

Table 10. Yield Results for Cotton--Condition Three

Year	Yield (lbs/acre)	Rainfall (inches)	Irrigation (inches)	No.	Runoff (inches)
1962	2788.70	22.09	12.45	8	7.29
1964	6392.49	32.13	15.11	10	19.33
1966	3852.61	24.67	12.12	8	9.75
1967	8323.98	34.66	13.51	9	22.40
1968	5239.61	28.50	12.43	8	12.66
1969	3021.83	22.95	14.45	9	8.87
	Six Year Yield Average 4936.54				

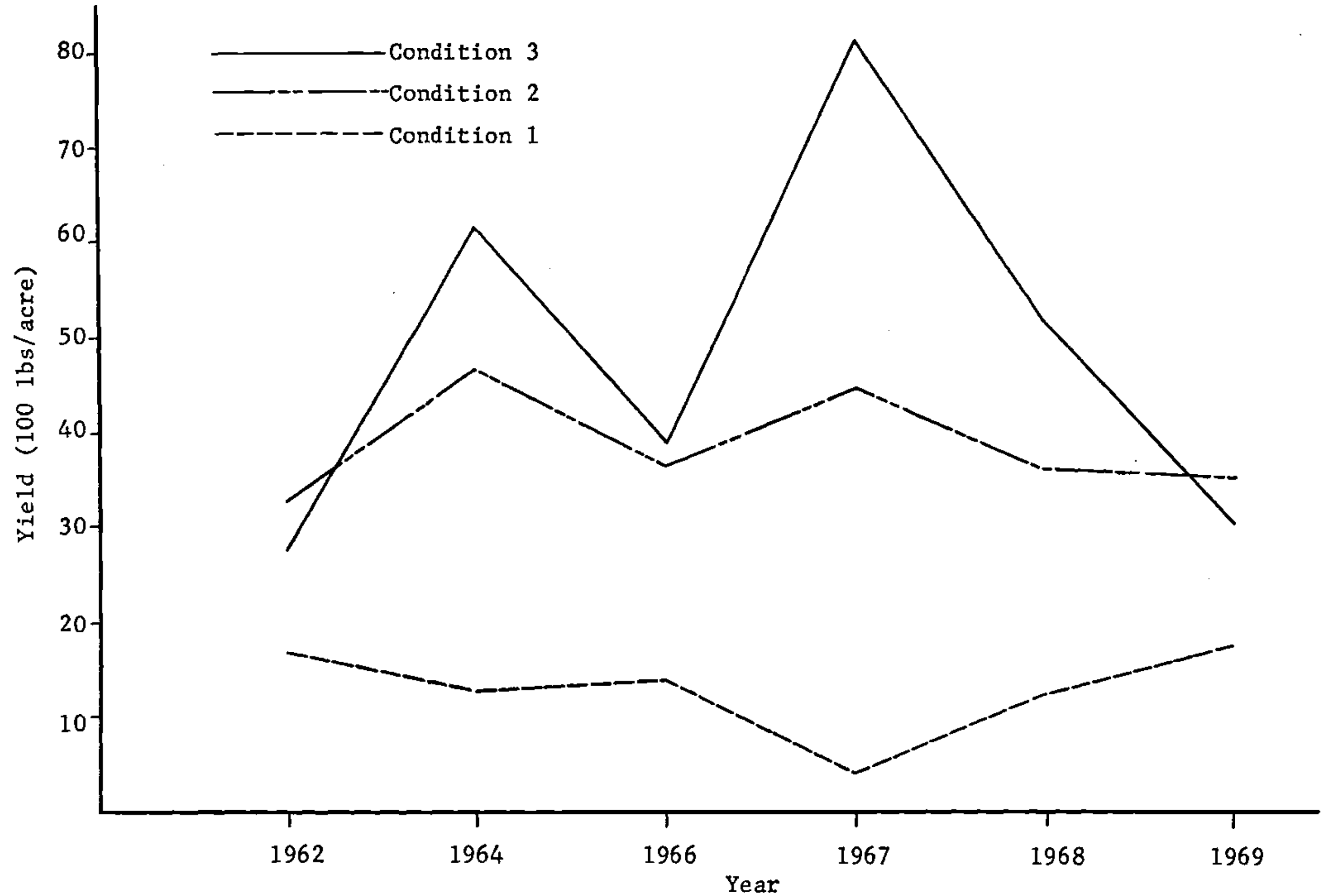

Figure 19. Cotton Production Results

provide adequate insect control, sufficient plant nutrients, weed control, and utilize high plant populations.

Tobacco Production

A lack in the amount and uniform distribution of rainfall during the growing season is a principal hazard affecting flue-cured tobacco production in Georgia. The data in Table 11, taken from the tobacco growth simulation as affected by natural rainfall, lend credibility to the fact that uneven distribution of rainfall and extended dry periods frequently cause wide fluctuation in tobacco yield. The results of the original irrigation tests on tobacco showed that the quality of the tobacco leaf is also affected by this moisture fluctuation. Tobacco growers have made substantiating reports in the past that tobacco grown during a dry season is very different from that grown during a season with ample moisture supply (34).

It is the desire of the tobacco farmer to produce a tobacco leaf during a season with sufficient and well-distributed moisture levels because the leaf produced is relatively large, light weight, thin, open-textured, elastic, light in color, and low in nicotine. These characteristics are the desirable qualities of a good tobacco leaf. While the yields presented in Table 12 and Table 13 show a striking difference in response to irrigation, the greatest improvement in yield came from the use of the closed-loop irrigation system. Since high moisture levels maintained by evenly distributed applications of water contribute to improving the quality of the tobacco leaf, then the improved yields obtained by the use of the closed-loop irrigation system would be made up of high

Table 11. Yield Results for Tobacco--Condition One

Year	Yield (lbs/acre)	Rainfall (inches)	Drought Days	Runoff (inches)
1962	1664.95	15.71	36	0.30
1964	418.17	28.32	31	10.11
1966	1614.37	17.56	29	1.19
1967	610.44	31.74	17	11.01
1968	1159.02	24.43	13	3.91
1969	1423.11	13.95	50	0.87
	Six Year Yield Average 1148.34			

Table 12. Yield Results for Tobacco--Condition Two

Year	Yield (lbs/acre)	Rainfall (inches)	Irrigation (inches)	No.	Runoff (inches)
1962	1681.69	15.71	4.95	6	0.30
1964	2337.88	28.32	4.65	5	10.11
1966	1904.92	17.56	1.30	2	1.19
1967	1382.22	31.74	1.95	2	11.01
1968	1159.02	24.43	0.00	0	3.91
1969	1699.56	13.95	3.30	4	0.94
	Six Year Yield Average 1694.22				

Table 13. Yield Results for Tobacco--Condition Three

Year	Yield (lbs/acre)	Rainfall (inches)	Irrigation (inches)	No.	Runoff (inches)
1962	4221.31	15.71	9.87	6	4.78
1964	6133.56	28.32	8.98	6	17.07
1966	4194.29	17.56	9.35	6	8.25
1967	4643.09	31.74	6.79	4	17.75
1968	3841.64	24.43	4.57	3	10.83
1969	4987.23	13.95	11.16	7	3.83
	Six Year Yield Average 4670.19				

quality tobacco leaf. It is evident from an analysis made of the conditions under which the original test was conducted that the yield differences in the simulation results can be directly attributed to the variations in rainfall, additions of supplemental water to the plants, and the timing factor.

The yields resulting from the occurrence of natural rainfall alone sometimes approximated the yields produced when supplemental water was added by manual irrigation practices. This is to be expected since, under proper distribution of rainfall, the excess water from manual supplemental irrigation might cause leaching of the soil nutrients and stunting of plant growth. Figure 20 provides a comparative plot of the results of tobacco yield as related to the three simulation conditions. The most significant increase in yield was obtained by controlling the supply of moisture by a closed-loop irrigation system. It is felt that such improved yields are attributed to the maintenance of adequate moisture levels in relation to the proper timing of the application of supplemental water.

Figure 20. Tobacco Production Results

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

As evidenced by the results from each crop simulation, there is a wide variation in the effects of a closed-loop irrigation system on crop yield. Since each crop has its own unit of measure for yield, it is appropriate to discuss the results of the simulation on a percentage of increase basis. Table 14 presents the total yield response for each crop as a percent increase over the total yield produced by natural rainfall which serves as the base of comparison. The yields produced by natural rainfall are assumed to be at the 100 percent level, and any fluctuation from this base is given as a percentage of these data.

Table 14. Comparative Yield Response (%)

	SYSTEM \ CROP	Tomato	Corn	Cotton	Tobacco	4-Crop Average
	Natural	100.00	100.00	100.00	100.00	100.00
I	Manual	127.39	198.75	166.82	147.54	160.12
	Closed-loop	146.33	462.08	219.66	306.69	283.69
II	Manual	100.00	100.00	100.00	100.00	100.00
	Closed-loop	114.87	232.50	119.80	176.65	160.95

In section I of the table the percent increase in yield resulting from supplemental irrigation over the yields produced under the conditions associated with natural rainfall are all significant. However, the largest increase occurs when the moisture level is controlled by a closed-loop irrigation system. In section II, the basis of comparison is changed to the manual system results. For each crop there is a definite improvement in yield that is related to the use of the closed-loop system. The percentage of improvement varies among the crops on which the system is used, but this is to be expected since each crop has individual characteristics for growth which may or may not be entirely related to the soil moisture content. If the moisture needs of the crop could be measured directly from the plant, it is doubtful that the variance in percentage improvement from crop to crop would be as great. However, since no practical or feasible method is available to adequately determine the moisture needs directly from the plant, it remains that the most efficient method for controlling field moisture levels is through the use of a closed-loop irrigation system with soil moisture sensing devices providing the control feedback information.

In conclusion, the overall results of the simulation show that an irrigation system operating in response to devices that sense the crop needs for water can more effectively meet those needs in excess of rainfall than any other system in use in the state of Georgia. The study indicates that there is definitely a significant improvement in crop yield when the crop production system is subjected to a more efficiently controlled moisture level input provided by a closed-loop irrigation system. It is felt that the results of this study also underscore the importance of the farmer's need for knowing when to irrigate and how much water to apply. In addition, if the outcome of this study opens the door to more efficient irrigation practices which will not only reduce the individual work load of the farmer but improve his economic position by increasing yields and reducing outside labor costs, then the thesis has made a contribution to improving agricultural production standards.

Recommendations

The estimated yields which have been produced as a result of the simulation can in no way be considered to represent the actual yields that a farmer can expect to produce by using such a system as proposed. There are several factors which have not been considered in this thesis which have an effect on the yield of crops. A thorough study of these factors, such as temperature, radiation, fertilizer, soil characteristics, the effect of insects, moisture, and their interrelationships, must be made in order to give a better approximation of estimated yield to actual yield. The ideal test of the system's effectiveness would be to actually plant crops in test plots and subject the crops to these three conditions over a long trial period. Such a study would require several years for the test to produce meaningful data which would be more reliable than a computer simulation based on empirical data, but an undertaking of this nature would be costly, time consuming, and difficult to manage. It is felt, however, that a computer simulation such as used in this study can be improved on by developing a better production function on which a comparison can be made. The function needs to be developed with a better analysis of the effects of all the variables on crop yield than was available at the time of this study. It is evident from the study of the original irrigation test results and reports that other factors may have equal or even greater effects on yield than moisture levels alone. A production function defined in relation to all these factors, or even the most significant ones, would probably produce a more precise comparative analysis of the effects of a closed-loop irrigation system on crop yield than was achieved in this thesis.

A future study of this system is recommended in relation to handling the effects of the closed-loop system on crop yield when consideration is given to the problems associated with frost and heat conditions and the application of insecticides, herbicides, and fertilizers. Since the farm of the future will require more efficient food production for the money invested, the irrigation system used in the production process will be required to be more efficient in applying water and to handle the demands related to minimizing crop damage due to heat, frost, insects, and weeds and to controlling nutrients in the soil.

APPENDICES

APPENDIX I

DEFINITION OF TERMS

Surface Irrigation. This type of irrigation considers the soil as a reservoir from which the plants obtain the water they need. The water is conveyed and distributed over the land by flooding, furrows, or corregation irrigation.

Sprinkler Irrigation. Water for the plants is conveyed above or below the field surface through pipes and is subsequently sprayed over the plants by sprinklers. The soil acts as the storage reservoir. Application methods include the cable-tow system, the center-pivot system, the lateral-move, the lateral-roll, the solid set, and the traveling gun system.

Subsurface Irrigation. This method introduces water into the soil through an underground porous pipe system. The capillary action of the water forces the water to the root system of the plant and to the surface of the soil to meet the needs of the crops. In effect, the soil maintains a high level of moisture content at all times.

Evapotranspiration Rate. This rate is considered to be a major factor in the design of irrigation systems which involve two interrelated processes. First is the evaporation of moisture from the soil surface and the plant surface. The second process is the transpiration or internal use of moisture by the plants.

Drought Day. A drought day occurs when there is insufficient soil moisture available for a 24 hour period in the root zone region for plant growth and development (35).

Wilting Point. The condition for wilting in plants is considered to be reached when the soil moisture level reaches 50 per cent of the field capacity. If the level of moisture drops below this point the plant will begin to suffer from the lack of adequate moisture. If this condition is permitted to continue then the plant will not produce a yield that could be otherwise expected.

Field Capacity. The maximum amount of moisture that a given soil will hold before becoming over-saturated. Moisture above this quantity is considered to be lost by either runoff or deep percolation. The capacity of soils are affected by texture, structure, and organic matter content.

Deep Percolation. This condition occurs when the depth of infiltrated water in an application exceeds the water holding capability of the soil for a given root zone depth of a crop under production. Losses due to this phenomenon are relatively small in most cases. When leaching of the soil is desired deep percolation is a beneficial occurrence.

Surface Runoff. The product of the application of water in excess of the soil intake rate. Drainage return flows may be designed to capture runoff and route it back to a reservoir for future use if such an approach is considered to be economically feasible and practical. Extreme amounts of runoff can be damaging to the soil and the crops under production.

APPENDIX II

CROP TEST DATA

Tomatoes

The data given in Table 15 were obtained from the results of a test treating the effects of irrigation on tomatoes which was conducted at Auburn University during the period 1940-1957. The experiment was administered under the conditions for no cover crop and for a vetch cover crop. The yield values for plots A and B in Table 15 are from the vetch cover crop only. In addition, the yields are the total yields for tomatoes grown on the plots and not the marketable yields. The size of the plots used in the experiment were 1/320th of an acre (36).

Corn

The results of tests on the effects of irrigation on corn given in Table 16 were obtained from the reports of irrigation studies conducted during 1947-1958 at Athens and Watkinsville, Georgia (37). The corn tests involved growing a stand of field corn on two separate test sites corresponding to two different types of soil. The bottomland test site was of the Congaree soil type and the upland site was of the Cecil soil type. In addition, Tennessee 10 hybrid corn was used during the 1946-1948 period inclusively. NC-27 hybrid corn was used during the test period from 1949-1955 inclusively. The data in Table 16 were limited to the period covering 1949-1955 in order to ensure that consistent conditions were available to which the crops were subjected during the tests.

Table 15. Tomato Test Data

Year	Plot	Rainfall (inches) X_1	Drought Days X_2	Irrigation (inches) X_3	Yield (Pounds/Plot)* With	Without
1940	A	12.20	37	5.00	144.06	151.67
	B	12.20	37	5.00	138.48	127.73
1941	A	8.34	43	6.00	125.47	96.09
	B	8.34	43	6.00	120.18	102.63
1942	A	12.43	34	5.00	79.60	59.96
	B	12.43	34	5.00	70.28	48.22
1943	A	8.56	45	4.00	56.23	29.98
	B	8.56	45	4.00	35.83	38.11
1955	A	13.39	18	4.00	137.90	81.34
	B	13.39	18	4.00	122.20	123.42
1956	A	7.30	45	10.50	164.52	124.26
	B	7.30	45	10.50	154.12	112.94
1957	A	21.31	4	5.25	139.28	93.86
	B	21.31	4	5.25	92.46	132.22

*Plot size = 1/320 acre

Table 16. Corn Test Data

Year	Rainfall (inches) X_1	Drought Days X_2	Irrigation (inches) X_3	Yield (bushels/acre) With	Without
1949	16.47	46	3.04	85.6	82.3
1950	16.65	60	1.50	74.4	57.7
1951	17.62	55	3.00	73.4	50.2
1952	8.10	85	10.94	70.1	10.6
1953	12.38	71	7.04	97.9	33.9
1954	15.47	63	5.16	96.5	63.8
1954	15.47	63	5.16	104.7	49.0
1955	17.52	61	8.35	129.9	53.8

Cotton

Studies of cotton irrigation were made on upland field plantings on Cecil soil at the Southern Piedmont Conservation Experiment Station from 1949 through 1957. The yields given in Table 17 are for seed cotton produced per acre under the test conditions (38).

Table 17. Cotton Test Data

Year	Rainfall (inches) X_1	Drought Days X_2	Irrigation (inches) X_3	Yield (pounds/acre) With	Yield (pounds/acre) Without
1950	25.77	60	1.50	1430	1087
1951	24.37	62	4.00	2538	2165
1952	16.93	99	8.62	2534	742
1953	19.64	114	9.91	1731	934
1954	18.94	87	4.66	1979	1395
1954	18.94	87	4.66	1998	1427
1955	18.81	89	6.48	3147	2383
1956	24.92	83	5.76	3621	1952
1957	22.89	78	12.54	3286	1844

Tobacco

An experiment designed in 1951 which continued through the 1954 season was conducted at the Coastal Plains Experiment Station, Tifton, Georgia, to obtain information concerning the use of supplemental water on yield and quality of flue-cured tobacco (39). Subsequent tests in 1960 and 1962 were conducted on the same soil and for the same crop to obtain up-dated results (40). Table 18 contains the results for all of those tests.

Table 18. Tobacco Test Data

Year	Rainfall (inches) X_1	Drought Days X_2	Irrigation (inches) X_3	Yield (pounds/acre) With	Yield (pounds/acre) Without
1951	17.67	40	5.00	1798	1297
1952	11.73	58	5.75	1277	1100
1953	21.47	16	2.75	1464	1448
1954	7.18	81	6.00	1434	1095
1960	11.74	51	5.55	1839	1772
1960	11.74	51	5.55	1808	1783
1962	9.35	69	8.29	2108	1674
1962	9.35	69	8.29	1992	1572

Crop Production Functions

The B coefficients for each regression equation representing the crop production function of each of the above crops were determined from a multiple regression analysis by means of the backward solution method. The equation for each crop is given as (8) for tomatoes; (9) for corn; (10) for cotton; and (11) for tobacco. In the process of determining the coefficients for cotton and tobacco the values for the yields were modified by dividing the yields by 100. This was done to simplify the numerical calculations involved in the inversion of the matrix needed for obtaining the coefficients.

Tomato Production Function

$$\hat{Y} = -542.26 + 40.51X_1 + 32.52X_2 + 13.07X_3 - 0.51X_1^2 - 0.34X_2^2 - 0.05X_3^2 - 1.15X_1X_2 - 0.45X_1X_3 \quad (8)$$

Corn Production Function

$$\hat{Y} = 313.06 - 17.95X_1 - 1.99X_2 - 3.15X_3 + 0.19X_1^2 \qquad (9)$$

$$- 0.02X_2^2 + 0.004X_3^2 + 0.16X_1X_2 + 0.21X_1X_3$$

Cotton Production Function

$$\hat{Y} = 6.15 + 0.229X_1 + 0.213X_2 - 0.079X_3 - 0.017X_1^2 \qquad (10)$$

$$- 0.003X_2^2 - 0.004X_3^2 + 0.011X_1X_2 + 0.037X_1X_3$$

Tobacco Production Function

$$\hat{Y} = 60.59 - 2.54X_1 - 0.27X_2 - 1.22X_3 + 0.03X_1^2 \qquad (11)$$

$$- 0.002X_2^2 + 0.007X_3^2 + 0.002X_1X_2 + 0.04X_1X_3$$

APPENDIX III

SIMULATION PROGRAM

```
C       THIS SIMULATION PROGRAM IS WRITTEN IN FORTRAN IV FOR USE ON THE
C       UNIVAC 1108 COMPUTER.  IT IS IN PARTIAL FULFILLMENT OF THE REQUIRE-
C       MENTS FOR A MASTER OF SCIENCE IN INDUSTRIAL ENGINEERING DEGREE AT
C       THE GEORGIA INSTITUTE OF TECHNOLOGY, ATLANTA, GEORGIA, BY JOHN H.
C       MATTHEWS.
C
C
C       THE FOLLOWING ABBREVIATIONS ARE USED IN THIS PROGRAM TO DEFINE THE
C       TERMS INDICATED.
C
C                 NAME                      MEANING
C
C                 DPR               DAILY PROBABILITY OF RAIN
C                 DRF               DAILY RAINFALL
C                 DSM               DAILY SOIL MOISTURE CONTENT (1)
C                 DMC               DAILY SOIL MOISTURE CONTENT (2)
C                 DSW               DAILY SOIL MOISTURE CONTENT (3)
C                 EXR               EXPECTED RAINFALL
C                 EVR               EVAPOTRANSPIRATION RATE (CONSTANT/MEAN)
C                 ETR               EVAPOTRANSPIRATION RATE (COMPUTED)
C                 SIG               VARIANCE OF EVAPOTRANSPIRATION RATE
C                 SIGMA             STANDARD DEVIATION OF EVAPO RATE
C                 SOILM             50% SOIL MOISTURE CAPACITY (WILTING PT)
C                 SMC               SOIL MOISTURE CAPACITY
C                 NGS               DAYS IN GROWING SEASON
C                 IDD               NUMBER OF DROUGHT DAYS
C                 RGN               AMOUNT OF IRRIGATION WATER APPLIED
C                 TTR               TOTAL TIME TO IRRIGATE (% OF GROWING
C                                       SEASON)
C                 TRGN              TOTAL WATER BY IRRIGATION
C                 NIR               NUMBER OF IRRIGATIONS
C                 RF                TOTAL SEASONAL RAINFALL
C                 ND                TOTAL GROWTH PERIOD IN DAYS
C                 IC                CROP TYPE
C                 TDPU              DEEP PERCOLATION OR RUNOFF
C                 KASE              METHOD OF WATER APPLICATION SIMULATED
C                                     (1)  RAINFALL ONLY
C                                     (2)  RAINFALL AND MANUAL SCHEDULE
C                                     (3)  RAINFALL AND CLOSED LOOP
C
C
C
        DIMENSION SIG(4),SMC(4),EXR(180),EVR(4),SOILM(4),DRF(180),DPR(180)
```

```
     *,DSM(180),C(4),AA(4),AB(4),AC(4),AD(4),AE(4),AF(4),AG(4),AF(4),DMC
     *(180),DSW(180)
      COMMON/BLOK A/IX
      COMMON/BLOK B/EVR, SIG,I
      COMMON/BLOK D/ETR
C
C     READ IN THE VARIANCE AND MEAN FOR EACH EVAPOTRANSPIRATION RATE AND
C         THE EXPECTED RAINFALL DATA AND THE SOIL MOISTURE HOLDING CAPAC-
C         ITY AND THE REGRESSION COEFFICIENTS FOR THE PRODUCTION FUNCTION
C         FOR EACH CROP SIMULATED.
C
      READ(5,80)(C(I),I=1,4)
   80 FORMAT(4F10.4)
      READ(5,80)(AA(I),I=1,4)
      READ(5,80)(AA(I),I=1,4)
      READ(5,80)(AB(I),I=1,4)
      READ(5,80)(AC(I),I=1,4)
      READ(5,80)(AD(I),I=1,4)
      READ(5,80)(AE(I),I=1,4)
      READ(5,80)(AF(I),I=1,4)
      READ(5,80)(AG(I),I=1,4)
      READ(5,80)(AH(I),I=1,4)
      READ(5,96)(SIG(I),I=1,4)
   96 FORMAT(4F5.3)
      READ(5,97)(SMC(I),I=1,4)
   97 FORMAT(4F5.2)
      READ(5,98)(EXR(J),J=1,180)
   98 FORMAT(20F4.2)
      READ(5,99)(EVR(I),I=1,4)
   99 FORMAT(4F5.2)
      READ(5,100)(SOILM(I),I=1,4)
  100 FORMAT(4F5.2)
      IX=3555339061
   10 READ(5,101,END=6)YEAR
  101 FORMAT(116)
C
C        INITIALIZE DATA FOR PRECIPITATION PROBABILITY FORECAST AND DAILY
C        RAINFALL FOR EACH YEAR SIMULATED.
C
      READ(5,102)(DRF(J),J=1,180)
  102 FORMAT(20F4.2)
      READ(5,103)(DPR(J),J=1,180)
  103 FORMAT(26F3.0)
      IC=0
   11 IC=IC+1
      KASE=0
      KASE=KASE+1
C
C        DETERMINE THE TOTAL NUMBER OF DAYS IN THE GROWING SEASON FOR THE
C        CROP STUDIED.
C
```

```
      IF(IC.EQ.1)NGS=88
      IF(IC.EQ.2)NGS=120
      IF(IC.EQ.3)NGS=160
      IF(IC.EQ.4)NGS=120
      I=IC
      TRGN=0.0
      TDPL=0.0
      TRF=0.0
      IDD=0
C
C        COMPUTE THE SOIL MOISTURE LEVEL FOR THE FIRST DAY OF THE GROW-
C        ING SEASON.
C
      DSM(1)=SOILM(I)-EVR(I)+DRF(1)
      DO 15 J=2,NGS
C
C        COMPUTE THE SOIL MOISTURE LEVEL FOR EACH DAY REMAINING IN THE
C        GROWING SEASON.
C
      DSM(J)=DSM(J-1)-EVR(I)+DRF(J)
      TRF=TRF+DRF(J)
      IF(DSM(J))13,12,12
   12 IF(DSM(J).GT.SMC(I))GO TO 14
      GO TO 15
C
C        CALCULATE THE TOTAL NUMBER OF DROUGHT DAYS.
C
   13 IDD=IDD+1
      DSM(J)=0.0
      GO TO 15
C
C        DETERMINE THE WATER LOSS DUE TO EITHER DEEP PERCOLATION OR TO
C        SURFACE RUNOFF.
C
   14 DPU=DSM(J)-SMC(I)
      TDPL=TDPL+DPU
      DSM(J)=SMC(I)
   15 CONTINUE
      RF=TRF+DRF(1)
C
C        COMPUTE THE CROP YIELD FOR THE RAINFALL CASE ONLY.
C
      YIELD=C(I)+AA(I)*RF+AB(I)*IDD+AC(I)*TRGN+(AD(I)*(RF**2))+(AE(I)*(I
     *DD**2))+(AF(I)*(TRGN**2))+(AG(I)*RF*IDD)+(AH(I)*RF*TRGN)
      IF(YIELD.LT.0.0)YIELD=0.0
      WRITE(6,200)
  200 FORMAT(103H     YEAR          YIELD            TOTAL RAINFALL     TOTAL
     *DROUGHT DAYS       RUNOFF        CROP TYPE      CASE)
      WRITE(6,201)YEAR, YIELD,RF,IDD,TDPL,IC,KASE
  201 FORMAT(//,I8,7X,F8.4,12X,F6.3,15X,I3,13X,F7.3,10X,I2,10X,I2,//)
C
C        INITIALIZE THE VARIABLES FOR MANUAL IRRIGATION.
C
```

```
      KASE=KASE+1
      CMA=0.0
      NIR=0
      TDPU=0.0
      ID=0
      ND=0
      RGN=0.0
      TTR=0.0
      TRGN=0.0
      DATUM=EVR(I)*2.0
C
C        COMPUTE THE SOIL MOISTURE LEVEL FOR THE FIRST DAY OF THE GROW-
C        ING SEASON.
C
      DMC(1)=DSM(1)
      DO 50 J=2,NGS
      GO TO (25,26,27,28),IC
C
C        MANUAL IRRIGATION REQUIREMENTS FOR TOMATOES.
C
   25 AMC=DMC(J-1)/SMC(I)
      IF(AMC.GT..25)GO TO 31
      GO TO 29
C
C        MANUAL IRRIGATION REQUIREMENTS FOR CORN.
C
   26 ND=ND+1
      TTR=FLOAT(ND)/FLOAT(NGS)
      IF(TTR.GT..40.AND.TTR.LT..45)GO TO 29
      IF(TTR.GT..499.AND.TTR.LT..501)GO TO 29
      IF(TTR.GT..58.AND.TTR.LT..62)GO TO 29
      GO TO 31
C
C        MANUAL IRRIGATION REQUIREMENTS FOR COTTON.
C
   27 ND=ND+1
      TTR=FLOAT(ND)/FLOAT(NGS)
      IF(TTR.GT..25.AND.TTR.LT..28)GO TO 29
      IF(TTR.GT..35.AND.TTR.LT..40)GO TO 29
      IF(TTR.GT..53.AND.TTR.LT..55)GO TO 29
      IF(TTR.GT..70.AND.TTR.LT..74)GO TO 29
      GO TO 31
C
C        MANUAL IRRIGATION REQUIREMENTS FOR TOBACCO.
C
   28 AMC=DMC(J-1)/SMC(I)
      ND=ND+1
      IF(AMC+CMA)34,34,31
   29 IF(DRF(J+1).GT.DATUM)GO TO 31
      IF(DMC(J-1).GT.1.2)GO TO 31
      RGN=1.3
      NIR=NIR+1
```

```
      GO TO 32
   31 IL=0
   37 RGN=0.0
C
C        COMPUTE THE SOIL MOISTURE LEVEL FOR EACH DAY REMAINING IN THE
C        GROWING SEASON.
C
   32 DMC(J)=DMC(J-1)+DRF(J)-EVR(I)+RGN
      TRGN=TRGN+RGN
      IF(DMC(J).GT.SMC(I))GO TO 33
      GO TO 50
C
C        DETERMINE THE WATER LOSS DUE TO EITHER DEEP PERCOLATION OR TO
C        SURFACE RUNOFF.
C
   33 DPU=DMC(J)-SMC(I)
      TDPU=TDPU+DPU
      DMC(J)=SMC(I)
      GO TO 50
   34 IL=IL+1
      IF(IL.GT.6)GO TO 30
      GO TO 37
   30 IL=0
      TTR=FLOAT(ND)/FLOAT(NGS)
      IF(TTR.GT..40.AND.TTR.LT..65)GO TO 35
      IF(TTR.GT..85)GO TO 36
      GO TO 40
   35 IF(DRF(J+1).GT.DATUM)GO TO 40
      RGN=1.0
      NIR=NIR+1
      GO TO 41
   36 IF(DRF(J+1).GT.DATUM)GO TO 40
      RGN=0.65
      NIR=NIR+1
      GO TO 41
   40 RGN=0.0
   41 CMA=AMC
      GO TO 32
   50 CONTINUE
   56 IF(TDPU.LE.TDPL)TDPU=TDPL
      IF(TRGN.LE.0.0)GO TO 57
      TRGN=TRGN*1.0
C
C        COMPUTE THE CROP YIELD FOR EITHER MANUAL FOR CLOSED-LOOP IRRI-
C        GATION.
C
      YIELD=C(I)+AA(I)*RF+AB(I)*ID+AC(I)*TRGN+(AD(I)*(RF**2))+(AE(I)*(ID
     ***2))+(AF(I)*(TRGN**2))+(AG(I)*RF*ID)+(AH(I)*RF*TRGN)
      TRGN=TRGN/10.0
      ID=0
      IF(YIELD.LT.0.0)YIELD=0.0
   57 WRITE(6,202)
```

```
  202 FORMAT(116H    YEAR          YIELD          TOTAL RAINFALL    TOTAL AM
     *OUNT IRRIGATION       NO OF IRR       RUNOFF      CROP TYPE   CASE)
      WRITE(6,203)YEAR,YIELD,RF,TRGN,NIR,TDPU,IC,KASE
  203 FORMAT(//,4X,I4,6X,F10.4,9X,F7.3,14X,I3,8X,F7.3,I9,I10.//)
      IF(KASE.EG.3)GO TO 61
C
C         INITIALIZE THE VARIABLES FOR THE CLOSED-LOOP SYSTEM.
C
      KASE=KASE+1
      TDPU=0.0
      TTR=0
      ND=0
      TRGN=0.0
      ETR=0.0
      RGN=0.0
      NIR=0
C
C         DETERMINE EVAPOTRANSPIRATION RATE FOR THE FIRST DAY OF THE GROW-
C         ING SEASON USING THE SUBROUTINE WHICH COMPUTES THE LOG-NORMAL
C         DISTRIBUTION.
C
      CALL VARIE
      CALL EVAPO
C
C         COMPUTE THE SOIL MOISTURE LEVEL FOR THE FIRST DAY OF THE GROW-
C         ING SEASON.
C
      DSW(1)=SOILM(I)-ETR+DRF(1)
      ND=1
      DO 60 J=2,NGS
      ND=ND+1
C
C         DETERMINE THE EVAPOTRANSPIRATION RATE FOR EACH SUBSEQUENT DAY.
C
      CALL EVAPO
C
C         COMPUTE THE SOIL MOISTURE LEVEL FOR EACH DAY REMAINING IN THE
C         GROWING SEASON.
C
      DSW(J)=DSW(J-1)+DRF(J)-ETR+RGN
      RGN=0.0
      IF(DSW(J).GT.SOILM(I))GO TO 58
      DATA=(SOILM(I)*2.0)/5.0
      IF(DSW(J).LE.DATA)GO TO 51
C
C         DETERMINE THE PROBABILITY OF RAIN AND THE EXPECTED QUANTITY OF
C         RAIN.
C
      IF(DPR(J+1).GT..30.AND.EXR(J+1).GT.EVR(I))GO TO 53
      IF(DPR(J+1).GT..20.AND.EXR(J+1).GT..75)GO TO 53
      IF(IC.GT.1)GO TO 51
```

```
      TTR=FLOAT(ND)/FLOAT(NGS)
      IF(TTR.GT..25.AND.TTR.LT..65)GO TO 59
      GO TO 51
   59 AMC=DSW(J)/SMC(I)
      IF(AMC.LE..25)GO TO 51
      GO TO 53
C
C        DETERMINE THE QUANTITY OF WATER TO BE APPLIED BY THE CLOSED-
C        LOOP IRRIGATION SYSTEM.
C
   51 IF(DRF(J+1).GT.0.0)GO TO 52
      RGN=SMC(I)-DSW(J)
      GO TO 54
   52 RGN=SMC(I)-DRF(J+1)-DSW(J)
   54 IF(RGN.LT.0.0)GO TO 53
      NIR=NIR+1
      TRGN=TRGN+RGN
      GO TO 58
   53 RGN=0.0
      GO TO 60
   58 IF(DSW(J).GT.SMC(I))GO TO 55
      GO TO 60
C
C        DETERMINE THE WATER LOSS DUE TO EITHER DEEP PERCOLATION OR TO
C        SURFACE RUNOFF.
C
   55 DPU=DSW(J)-SMC(I)
      TDPU=TDPU+DPU
      DSW(J)=SMC(I)
   60 CONTINUE
      GO TO 56
   61 IF(IC.EQ.4)GO TO 10
      GO TO 11
    6 STOP
      END

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

C
C
C                            A RANDOM NUMBER GENERATOR
C
C
      SUBROUTINE RANDOM
      COMMON/BLOK A/IX
      COMMON/BLOK C/RNUM
      IX=MOD(1025*IX+150001,2**20)
      RNUM=FLOAT(IX)/(2.0**20+1.0)
      RETURN
      END

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

```
C* * * * THIS ROUTINE COMPUTES THE VARIANCE FOR THE EVAPO ROUTINE * * * *
C
C
      SUBROUTINE VARIE
      DIMENSION EVR(4),SIG(4)
      COMMON/BLOK B/EVR,SIG,I
      COMMON/BLOK E/YMU,SIGMA
      VARY=ALOG(SIG(I)/(EVR(I)**2))+1)
      SIGMA=SQRT(VARY)
      YMU=ALOG(EVR(I))-(0.5*VARY)
      RETURN
      END

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

C* * * THIS ROUTINE COMPUTES THE LOG-NORMAL EVAPOTRANSPIRATION RATE * * *
C
C
      SUBROUTINE EVAPO
      COMMON/BLOK C/RNUM
      COMMON/BLOK D/ETR
      COMMON/BLOK E/YMU,SIGMA
      CALL RANDOM
      AVE=YMU+(RNUM*SIGMA)
      ETR=EXP(AVE)
      RETURN
      END
```

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