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The development of a framework for managing water resources: Irrigation development in Saginaw Bay, Michigan

He, Chan Sheng, Ph.D.

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U·M·I
300 N. Zeeb Rd.
Ann Arbor, MI 48106

THE DEVELOPMENT OF A FRAMEWORK FOR MANAGING WATER RESOURCES: IRRIGATION DEVELOPMENT IN SAGINAW BAY, MICHIGAN

By

Chan Sheng He

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ABSTRACT

THE DEVELOPMENT OF A FRAMEWORK FOR MANAGING WATER RESOURCES: IRRIGATION DEVELOPMENT IN SAGINAW BAY, MICHIGAN

By

Chan Sheng He

This study develops a framework for use by decision makers in the water resource management area. It focuses on irrigation development in the Saginaw Bay area of Michigan. The components of the framework include the: (1) estimation of crop irrigation requirements, (2) evaluation of groundwater sustainability for irrigation, (3) assessment of streamflow capacity for irrigation, (4) optimization of expected irrigation returns, and (5) spatial distribution of irrigation development.

Crop growth simulation models are used to simulate yields and irrigation water requirements of corn, soybeans, dry beans, and sugarbeets based on 30-year data on weather, soil, and management practices. A hydrologic budget equation, well log records, and partial chemistry data were used to evaluate the sustainability of groundwater and streamflow for irrigation supply. Optimization models, which incorporate the simulated crop yields, irrigation requirements, and streamflow availability, were established to develop spatially-oriented irrigation scenarios. The results indicate that irrigation may increase yields of corn, soybeans, dry beans and

sugarbeets by a large margin over non-irrigated identical plantings in the study area. The available streamflow may be sufficient to supply a maximum irrigation acreage of 44,000 acres, which is only 2 percent of the total agricultural land in the study area. Use of groundwater for irrigation should be practiced cautiously since continuous pumping would reduce discharge to streamflow and also induce upward movement of brine from deeper aquifers. Currently, there is increasing evidence that growers and decision makers will apply pressure to greatly exceed the available irrigation acreage. This study demonstrates such an expansion is not sustainable and could lead to the degradation and depletion of groundwater and streamflow and to the destruction of fisheries habitat. The optimal irrigation scenarios, given the assumptions of linearity and uniformity employed in this study, indicate that acreage of corn may be expanded and that irrigation priority be given to dry beans.

Computer simulation and optimization models and Geographic Information Systems are shown to be useful tools in supporting decision making for water resource management. The framework established in this study demonstrates the viability of using simulation models for policy aides. It also shows that models, to be used in irrigation planning, should have a sound physical basis and should first be validated in the field.

To my wife, Zhizhen, and my son, Bo.

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I would especially like to thank the other members of my graduate committee: Dr. Thomas Edens, Dr. Roger Wallace, and Dr. Baxter Vieux. In addition to serving as principal investigator on three grants which lead to the completion of this endeavor, Dr. Edens spent much of his time with me in finalizing this work. His support and dedication to this work are greatly appreciated. Dr. Wallace, despite his extremely busy schedule, guided me in the hydrogeologic analysis of this research. Finally, Dr. Vieux continued to serve as my graduate committee member even after he left Michigan State University. Working with the three of them was intellectually stimulating and rewarding.

Special thanks also go to my host family, Mr. and Mrs. Jack Bails. Their encouragement, care, and warm friendship have added much joy and happiness to my stay in the United States.

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Finally, I am grateful to my parents for their encouragement and support. I especially appreciate the values and beliefs they taught me during my growth, which laid the foundation for my development. Thanks also go to my little boy, Bo, whom I had not seen for four years during my study in the United States. He has given me much joy and happiness since he came to the United States in 1990. Lastly, special thanks go to my wife, Zhizhen, for her dedication, encouragement, and support. While working on her M.S. degree in Civil Engineering, she has sacrificed so much to help me complete this work. I attribute many of my achievements to her, my wonderful partner.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Management of limited water resources is one of the most important challenges in modern society as multiple demands have been placed on water for food production, industrial development, hydropower generation, transportation, waste disposal, recreation and maintenance of the ecosystem. These competing uses must be examined against the available sources to avoid over-withdrawal of these precious water supplies. This study develops a framework for an adaptive water resource management system to estimate crop irrigation requirements and to examine the availability of water resources for irrigation supply to support the wise use of the available water resources in humid and semi-humid areas.

An adequate supply of water is essential to ensure the success of agricultural production. One important way by which crops obtain water is through irrigation. Irrigated land accounts for 16 percent of the world's total cultivated area (Mather, 1984). In the United States, irrigation has become a crucial factor in the nation's agricultural output. It accounts for 13 percent of the nation's harvested cropland and contributes approximately 30 percent of the value of agricultural production (Negri and Hanchar, 1989). The total acreage of irrigated land, which has tripled since 1940, is still increasing in the United States (Gibbons, 1986).

Irrigated agriculture consumes the largest portion of the United States' water resources. In 1985, total freshwater consumption in the United States was estimated at 103 million acre-feet, of which irrigation accounted for approximately 83 percent[1] (Negri and Hanchar, 1989). Irrigated agriculture faces competition from alternative uses of water resources. First, as the population expands and industry grows, the demand for water for municipal supply, industrial development, waste disposal, navigation, and hydroelectricity increases. Second, over the past two decades, an increasing environmental awareness and the desire for outdoor recreation have also resulted in higher nonuser values for the instream use of water resources. Of particular importance is the growing recognition that instream water has value for water quality improvement, fish propagation, recreation and the maintenance of wildlife habitat. Due to the uneven distribution of water resources, these competing demands have led to significant over-development of existing water supplies in many areas, including the "mining" of streams and aquifers, the loss of

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[1]One acre-foot is the amount of water needed to cover an acre of land to a depth of 1 foot.

wetlands, and the destruction of fisheries and wildlife habitat (Mather, 1984).

The development of irrigation remains vital to the western United States, although the region will not experience a continuous growth of irrigated agriculture due to the limits established by the available water supply. The potential for agricultural irrigation expansion lies in humid and semi-humid areas of the country (Mather, 1984). Thus, it is anticipated that there will be a shift of new irrigation enterprises from the drier states to the humid or semi-humid regions (Mather, 1984). Unlike irrigated agriculture in arid or semiarid areas where no profit can exist without irrigation, irrigation in humid areas supplements precipitation. The timing and quantity of irrigation must be carefully scheduled in humid areas to maximize the profitability of crop production. As irrigation expands in humid areas, the availability of irrigation water must be examined in the context of multiple demands for water and alternative allocation methods to ensure sustainable use of the available water resources.

The Saginaw Bay Watershed, located in the east central portion of Michigan's lower peninsula, is the largest watershed in Michigan and covers a land area of approximately 8,072 square miles (Figure 1). The watershed provides a variety of recreational and industrial opportunities and many services for Michigan residents.

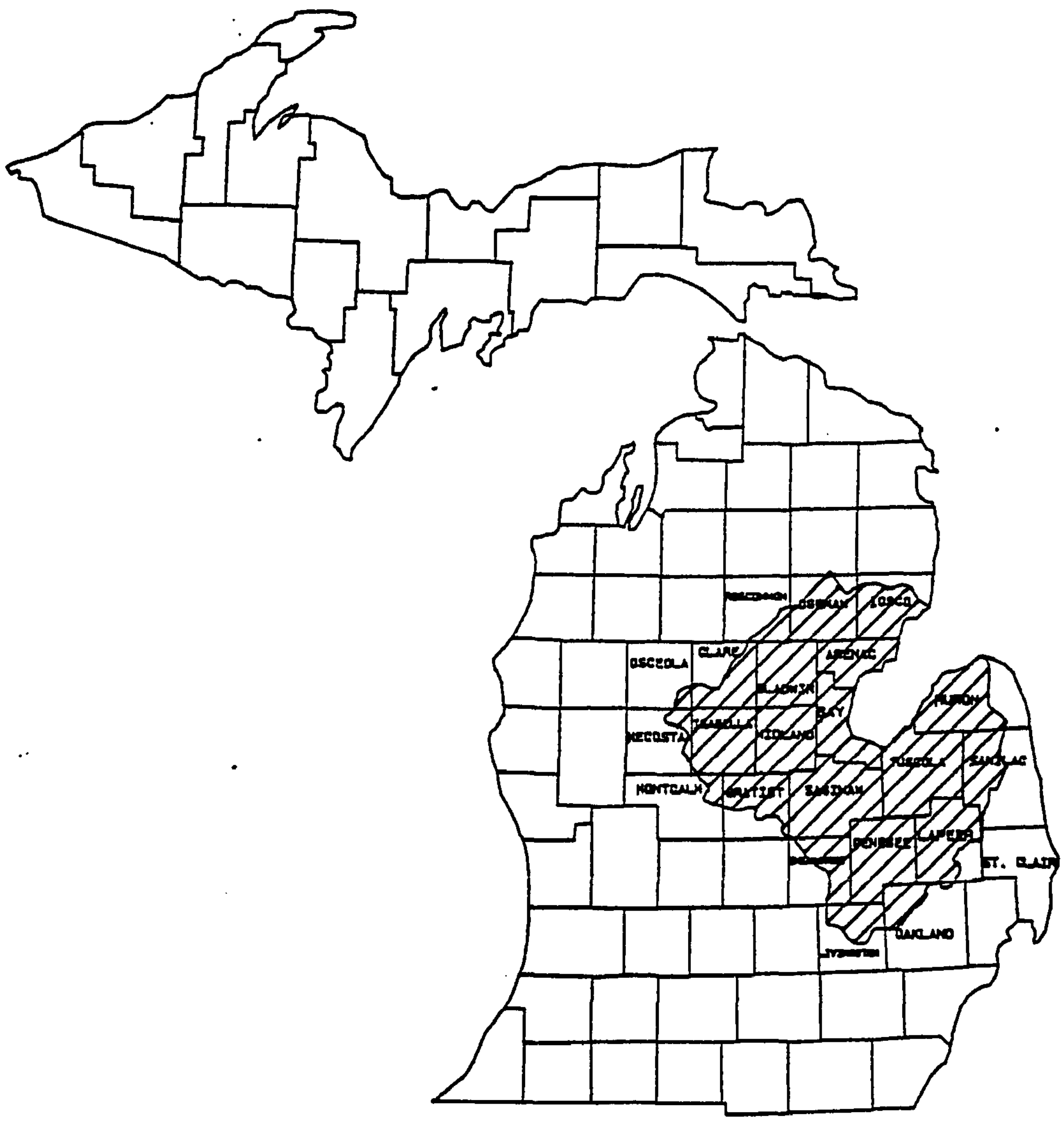

Figure 1. The Saginaw Bay Watershed Boundary (Shaded Area)

Water from Saginaw Bay supplies 45 drinking water distribution systems serving over 300,000 people. The Bay also supports commercial and recreational fisheries and other types of recreation. Nearly 50 percent of Michigan's 750,000 registered boats are located within 100 miles of Saginaw Bay, and 80 percent of Michigan's population lives within one hour's driving time. The watershed assimilates the flows of 67 municipal waste-water treatment facilities as well as hundreds of industrial waste treatment systems. In addition, the Bay is valuable to wildlife as a major fish spawning and nursery area, and it provides shelter and food for waterfowl on a major migratory flyway (Michigan Department of Natural Resources, 1988; Michigan Sea Grant College Program, 1990).

The Saginaw Bay Watershed is also one of the most productive agricultural regions in Michigan. Agriculture is a major contributor to the region's economy. In recent years, agricultural irrigation has rapidly expanded in the region. However, due to increasing demands for water for municipal uses, industrial development, waste disposal, aesthetic and recreational use, and fisheries and wildlife habitat protection, agricultural irrigation faces ever increasing competition for the available water resources. Without an overall management system, these competing demands may lead to over-development of the existing water resources. As a result, the depletion of streams and aquifers and the destruction of fisheries and wildlife habitat will likely occur. To assure sound economic development and sustainable use of the existing water resources, a systems approach[2] must be taken to assess the multiple demands for existing water resources to establish a balance between the various competing demands for water.

This study takes a systems approach to develop a framework for managing water resources for irrigation development in humid and semi-humid areas. The components of the framework to be developed include (1) examination of the complex relationships of crop irrigation water requirements and climate, soils, land use, and crop management, (2) evaluation of the water resources available for irrigation supply using a mass balance approach[3], and (3) development of optimal irrigation scenarios for sustainable use of the available water resources. The Saginaw Bay Watershed is chosen as the study area of this research.

Once a framework for water resource management has been developed, there is a good chance that wise resource use

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[2]The systems approach assumes the holistic investigation of objects as a whole but also their separation into subsystems and elements, which facilitates the investigation of the structure, organization and functional behavior of an object (Votruba et al., 1988).

[3]The mass balance approach or mass budget method is based on the principle of conservation of mass applied to some part of the hydrologic cycle. Conservation of mass, formulated as a mass budget equation, requires that for any given control volume, the inflow rate minus the outflow rate equals the rate of change of the water stored.

decisions will be made to ensure sound economic development along with the sustainable use of the available water resources. The framework developed from this study in the Saginaw Bay area of Michigan may also be applicable to practices of irrigation in other humid and semi-humid regions around the country.

CHAPTER 2

PROBLEM STATEMENT AND RESEARCH DESIGN

1. BACKGROUND

The Saginaw Bay Watershed is chosen as the study area to develop a framework for managing water resources for irrigation development. The watershed, located in the east-central portion of the lower peninsula of Michigan, is one of the most important resources in Michigan. It covers a land area of 8,709 square miles (22,557 km^2) and accounts for 15% of Michigan's total land area. The watershed includes portions of 22 of Michigan's 83 counties and supports a population of 1.5 million people. There is a diversified industrial infrastructure in the watershed, ranging from automobile manufacturing to food processing. The watershed contains the largest coastal wetland complex in Michigan and provides an outstanding habitat for fisheries and wildlife. Over 90 fish and 259 vertebrate species have been recorded in Saginaw Bay, and more than 20 species of waterfowl use Saginaw Bay habitats during the breeding and migration season (Michigan department of Natural Resources, 1988). The watershed also offers excellent recreational opportunities. The total value of the Bay sport fishery alone is estimated at several millions of dollars annually. In addition, the watershed is used for commercial navigation and waste disposal. Commercial freight traffic in the Saginaw River alone totals over 2 million tons per year. Currently, 211 industrial and municipal facilities discharge their waste waters into the watershed (Michigan Department of Natural Resources, 1988).

Agriculture is the most extensive single category of land use in the Saginaw Bay Watershed. A recent survey by He et al. (1992) indicates that agriculture is perceived as the most important sector in the region's economy. Cropland, totaling 3,300,000 acres, accounts for 59 percent of the total land area in the watershed. In recent years, the watershed has been targeted for irrigation expansion based on soil properties. There are a potential 1.67 million acres of land suitable for subsurface irrigation expansion. The water management system, formerly used exclusively for drainage, is now being used for irrigation as well. At the same time, local and regional communities are undergoing major economic readjustments in response to the recent decline in automobile manufacturing and associated businesses. These communities are moving rapidly to enhance tourism and light industries to take advantage of the water resources in the region. Environmental groups are also actively promoting the instream uses of water for recreation and aesthetics, and for fisheries and wildlife habitat. Unfortunately, these water uses compete with each other. As population grows, the need for water for enhanced food production, industrial development, hydropower generation, navigation, aesthetic and recreational uses, and ecosystem maintenance will increase. There is already increasing concern that inland water resources may not be sufficient to support these competing demands. Over-withdrawal of streamflow or groundwater may lead to their depletion as well as to degradation of water quality and destruction of fisheries and wildlife habitats. A framework must be developed to examine the inter-relationships of these competing demands and the available water resources to avoid adverse human, physical and ecological impacts resulting from over-withdrawal of the water resources.

This research develops a framework for an adaptive water resource management system. The framework will examine the complex inter-relationships among irrigation water requirements, climate, soils, land use, and available water resources as part of a systems approach. Once this framework has been developed, the requirements for available water resources for irrigation, the alternative crop mixes and the optimal acreage of irrigation can be evaluated prior to extensive investment in irrigation. In this manner, land and water resources can be better utilized, and over-development of irrigation can be avoided.

2. PROBLEM

Inland water resources in the Saginaw Bay area do not appear sufficient to support the potential increases in irrigation supplied by groundwater and streamflow. There is evidence that potential use significantly exceeds water availability (He et al., 1990 and Sweat, 1992).

In order to address this type of problem, it is first necessary to establish several related parameters. These include:

A. Irrigation water requirements,

B. Groundwater sustainability for irrigation,

C. Streamflow capacity for irrigation,

D. Optimal crop mix for maximizing expected water use returns, and

E. Spatial distribution of irrigation expansion.

This study develops a framework for addressing this class of water resource problems. Although <u>it will not provide a definitive answer</u> for the case study chosen here, it will serve to provide an exportable template which can be used to resolve these types of water resource issues.

3. RESEARCH DESIGN

3.1 Description of the Irrigation System

The irrigation system examined in this study is an agricultural crop production system in the Saginaw Bay

Watershed, Michigan. The study area encompasses Bay, Huron, Saginaw, Sanilac, and Tuscola Counties[4](Figure 2). This area is being targeted for irrigation expansion, especially for subsurface irrigation. The five county irrigated acreage has expanded from 8,460 acres in 1978 to 15,035 acres in 1987 (Bureau of the Census, 1984 and 1989). Based on soil suitability, the potential exists for as many as 1,667,000 acres of subsurface irrigation expansion, which accounts for 85 percent of the total agricultural land in the five county area (Kittleson et al., 1987).

Agriculture and forestry are two major land uses in the study area, accounting for 79 and 14 percent of the total land area (2,500,000 acres), respectively (Figure 3). Soils in the study area consist mainly of loam, silty clays and sandy loam, and are poorly drained in much of the area.

Crops being studied include corn, soybeans, dry beans, and sugarbeets. The harvested acreage of each of the four crops accounts for 33.5, 19.4, 17.2, and 9.3 percent, respectively, of the total crop acreage harvested between 1985 and 1989 (Michigan Department of Agriculture, 1986-1990). The irrigation season typically runs from June through August.

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[4]The five county study area is a portion of the Saginaw Bay Watershed, which includes 22 counties. The study area corresponds to the USDA Soil Conservation Service Saginaw Bay Subirrigation and Drainage Project Area. The five county area in this paper is referred to as the "Saginaw Bay area."

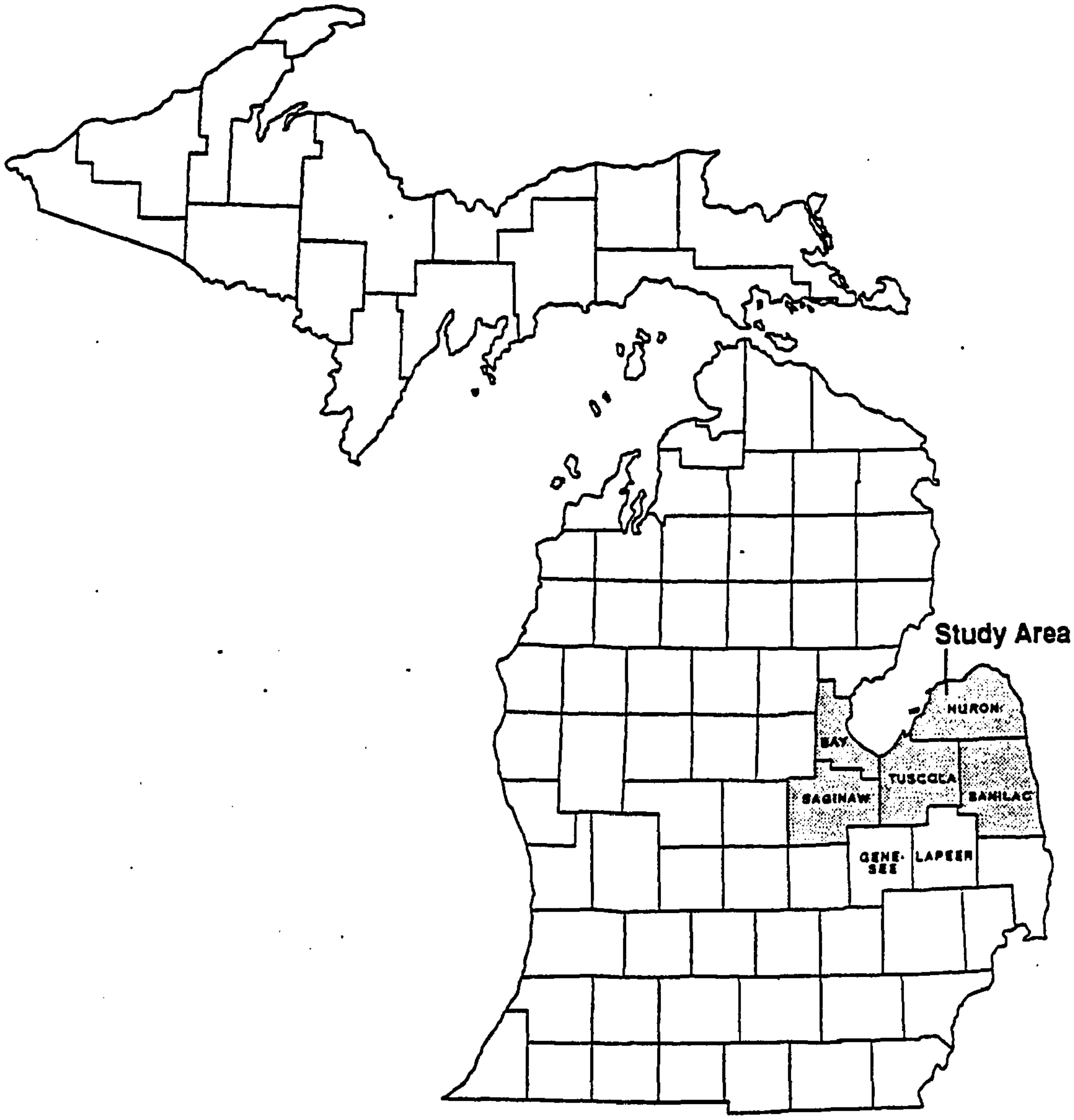

Figure 2. The Saginaw Bay Study Area

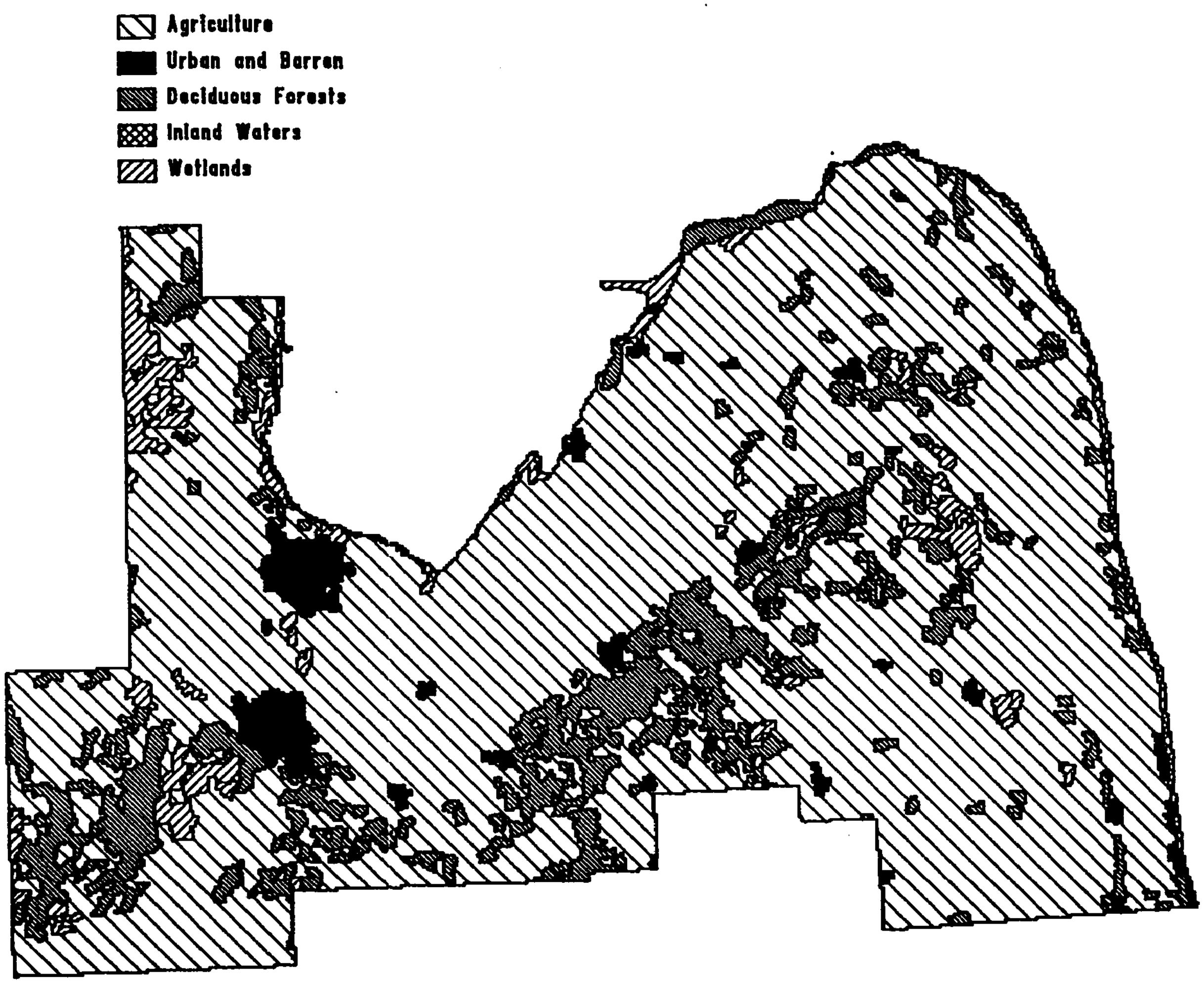

Figure 3. Land Use in the Saginaw Bay Area of Michigan

3.2 Flowchart and Scope of Work

Figure 4 illustrates the design of this study. It represents the integration of the five crop simulation and optimization models, along with the mass balance equation for assessing the capacity of groundwater and streamflow for irrigation. Four simulation models are used to estimate the evapotranspiration rates, irrigation water requirements and yields of corn, dry beans, soybeans and sugarbeets. Spatial and temporal variations in weather and soils are considered in estimating these parameters on the regional scale. The sustainability of groundwater for irrigation supply is evaluated in this study by examining the groundwater recharge rate, flow direction and quality. The capacity of streamflow for irrigation supply is evaluated in the mass balance equation to determine if the available water resources are sufficient to meet the crops' irrigation water requirements. Optimization models are developed to optimize the crop mixes for maximizing the expected returns from irrigation. Geographic Information Systems (GIS) are used in this study to process and analyze the data sets of land use, soils, and hydrogeology to provide inputs to the simulation and optimization models. Spatial distribution of the simulated results are processed by GIS at the watershed scale.

The scope of this study is the integration of the crop simulation and optimization models along with the mass

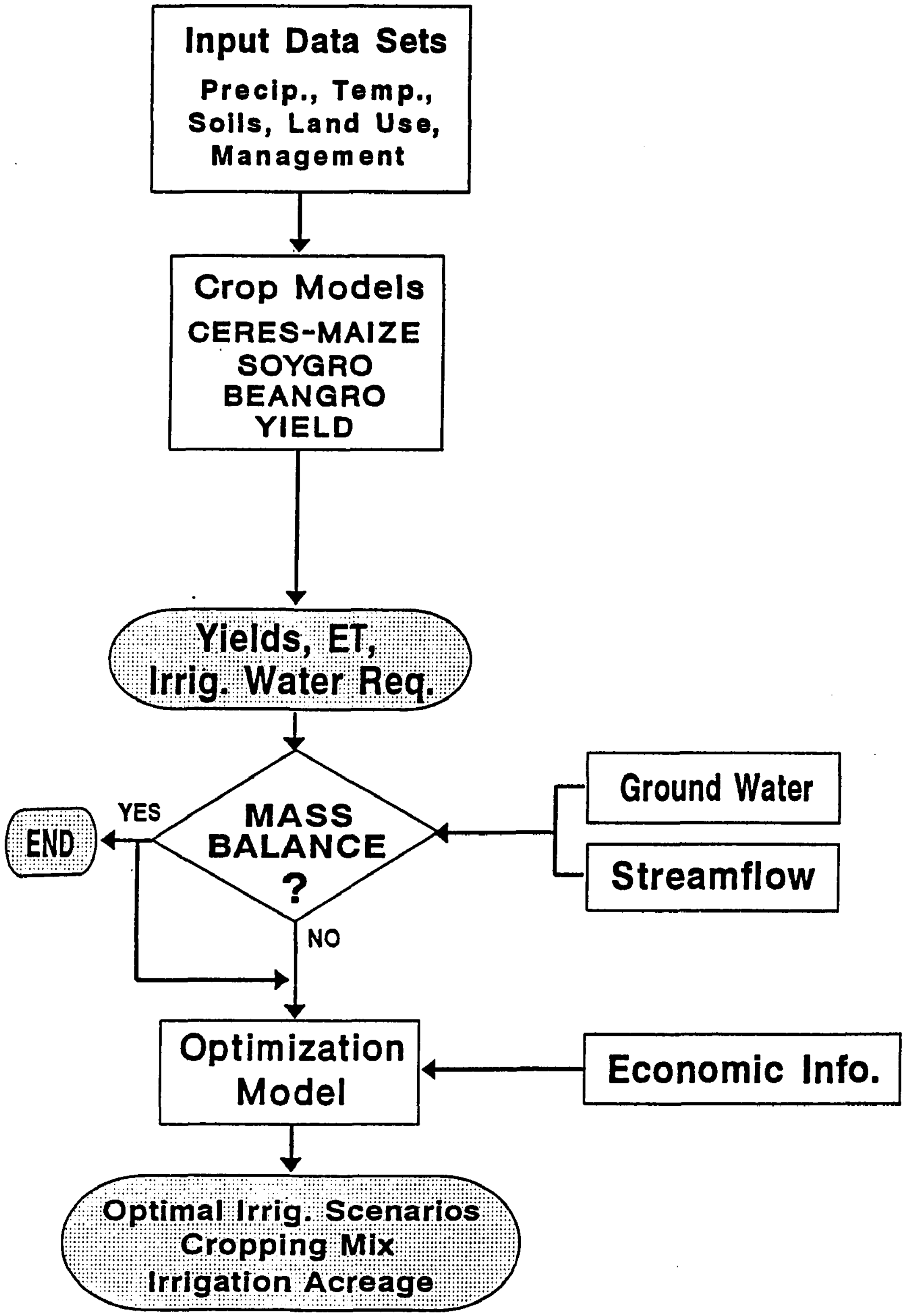

Figure 4. Flowchart of Water Resource Management System for Irrigation Development

balance equation for evaluating the availability of water resources for irrigation supply at the regional level. On-farm allocation and operation of irrigation is beyond the scope of this study. In addition, detailed hydrogeologic or geophysical investigations are not the subject of this study. Likewise, the quality of streamflow for the purpose of irrigation is not evaluated in this study, since the streamflow in the study area is generally of good quality for agricultural irrigation.

4. SYSTEM MODELING

The major components of system modeling in the framework are described below:

4.1 Estimation of Irrigation Water Requirement

The requirement for irrigation, which is the difference between the crop need and the amount of available soil moisture, is first estimated. Factors affecting the irrigation water requirement are considered, which include temperature, precipitation, solar radiation, soil texture and depth, land use activities, and management practices. Data sets of weather, soils, and management factors were acquired from the Michigan Department of Agriculture Climatology Program; the Michigan State University Nowlin Chair's Office and the USDA Soil Conservation Service; and the Huron County Cooperative Extension Service, respectively. These data sets were used in the crop simulation models to estimate irrigation water requirements for corn, soybeans, dry beans, and sugarbeets.

The crop growth simulation models used in this study include CERES-MAIZE (Ritchie et al., 1989) for corn, SOYGRO (Jones et al., 1989) for soybeans, and BEANGRO (Hoogenboom et al., 1990) for dry beans. They use daily weather data, soil characteristics, and management information to estimate crop yields and irrigation requirements.

The YIELD model (Schultink et al., 1989) is used to estimate the yield and irrigation water requirement of sugarbeets. It is based on one of the FAO's methods for estimating the potential crop yield, evapotranspiration rate, and irrigation requirement (Doorenbos and Kassam, 1979). Inputs to the model include daily or monthly mean temperature, precipitation, solar radiation, wind speed (at 2 m height), and relative humidity.

4.2 Evaluation of Groundwater Sustainability for Irrigation

Groundwater is used for domestic use and agricultural irrigation in the Saginaw Bay area. The sustainability of groundwater for irrigation is evaluated in this study by examining the groundwater recharge and discharge rates, flow direction and quality. A hydrologic budget is used to estimate the groundwater recharge and discharge rates in the study area. Well log records are used to derive the potentiometric surfaces of water in drift and bedrock aquifers to determine the direction of groundwater flow. Concentrations of dissolved solids, chloride and sodium are used to evaluate the quality of groundwater for irrigation.

4.3 Assessment of Streamflow Capacity for Irrigation

Use of surface water may increase the available water supply for agricultural irrigation. However, since the withdrawal of water from the Great Lakes for irrigation is legally restricted, streamflow availability needs to be examined in evaluating irrigation expansion. This study uses a mass balance approach to compute the streamflow available for irrigation and the maximum irrigation acreage that streamflow can sustain at the 90, 75 and 50 percent exceedence flow levels.[5]

4.4 Maximizing Expected Water Use Returns

Allocating limited water resources among different crops for irrigation is a typical resource use decision. Decision makers must determine which crops to irrigate, where to irrigate, and how much land to irrigate. The use of optimization techniques can help decision makers achieve the

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[5]The exceedence flow indicates the probability level at which streamflow will exceed or equal the specified value.

most satisfactory results while meeting resource and activity constraints.

In this study, linear programming models are developed to generate irrigation scenarios for use by decision makers as part of the basis for making resource use decisions. The models incorporate irrigation water requirements, available water resources, simulated crop yields, and expected returns to maximize total expected economic returns from the crops in the study area.

4.5 Spatial Distribution of Irrigation Expansion

Spatial distribution of irrigation expansion in the Saginaw Bay area is essential information to decision makers in water resource planning and management. Geographic Information Systems[6] are used in this study to derive inputs from the data sets of land use, soil associations, watershed boundaries, well log records, and hydrogeologic settings of the study area, to the simulation and optimization models as well as the water balance equation. The spatial distribution of the simulated irrigation requirements, potential irrigation expansion areas, and

[6]A Geographic Information System (GIS) is a system of computer hardware, software, and procedures designed to support the capture, management, manipulation, analysis, medullary and display of spatially referenced data for solving complex planning and management problems (Antenucci et al., 1991).

optimal crop mixes is processed by GIS at the watershed scale for display.

5. ASSUMPTIONS

It is assumed in the four simulation models that the four crops are not affected by pests and diseases. In addition, the irrigation requirement of crops does not include the loss of water during the delivery process. This loss should be considered in designing the irrigation pipe system. Furthermore, it is assumed that no advection exists since irrigation in a small scale would not result in the significant modification of the air movement. Thus, the irrigation water requirement per acre of land for the same crop on the same soil association is assumed the same regardless of the field size. In other words, uniformity and linearity are assumed for the same soil association.

Precipitation is assumed to be the only input to a watershed in estimating the groundwater recharge rate. Streamflow available for irrigation withdrawal is assumed to be the amount of water above the 95 percent exceedence flow level set by the National Pollutant Discharge Elimination System (NPDES).

Linearity is assumed in developing irrigation scenarios. That is, the expected returns from the crops increase linearly with the expansion in crop acreage. No economy of scale is considered in this study.

CHAPTER 3

LITERATURE REVIEW

1. ESTIMATING IRRIGATION WATER REQUIREMENTS

The requirement for irrigation is defined as the difference between the water needs of the disease-free crop and available soil moisture and effective precipitation[7] (Bartholic et al., 1983). Data on soil moisture and precipitation can be readily acquired from government agencies such as the U.S. Department of Agriculture Soil Conservation Service and the National Weather Service. The regional water requirements for each crop, however, are not readily available from government agencies or research institutions. They have to be calculated by determining the evapotranspiration rates of each crop assuming that they are grown in large fields under optimal soil conditions.

Evaporation is defined as the removal of water from soil or water surface by the conversion of liquid into vapor. The vaporization of water through the stomata of living plants is called transpiration. Since over-land transpiration from vegetation and direct evaporation from the soil are

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[7]Effective precipitation = total precipitation - surface runoff - deep percolation

difficult to separate, they are often combined together and are referred to as evapotranspiration which is defined as the total amount of water lost to the atmosphere through transpiration, plus the evaporation of water from the surrounding soil surface. Potential evapotranspiration is defined as the evapotranspiration rate of a disease-free crop growing in large fields under optimal soil conditions, including sufficient water and fertility and achieving full production potential under the given growing environment (Doorenbos and Pruitt, 1977).

Many methods have been developed to estimate the evapotranspiration rate of plants (Bowen, 1926; Blaney and Criddle, 1950; Makkink, 1957; Van Bavel, 1966; Fuchs and Tanner, 1967; Bartholic et al., 1970; Camillo et al., 1983; and Shayya and Bralts, 1989). A classic work by Penman (1948) combined aerodynamic heat and water vapor transport equations with the energy balance approach[8] to estimate evaporation from open water. Inputs to Penman's equations include the mean surface temperature, air temperature, mean dew point temperature, mean wind velocity, and the mean duration of sunshine.

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[8]The energy balance for a given system at the earth's surface is expressed as: $Rn = LE + H + G$ where Rn is the specific flux of net incoming radiation, L the latent heat of evaporation, E the rate of evaporation, H the specific flux of sensible heat into the atmosphere and G the specific flux of heat conducted into the earth, assuming that the effects of unsteadiness, ice melt, photosynthesis and lateral advection can be neglected.

Doorenbos and Pruitt (1977) modified the Penman method to take into account the effect of crop characteristics (via crop coefficients), including growth stages, on the potential evapotranspiration rate of the crop.

Based on the modified Penman method, Doorenbos and Kassam (1979) integrated the relationships between crop, climate, water and soil to quantify maximum and actual crop yields, maximum and actual evapotranspiration, and irrigation water requirements. The maximum yield of a particular crop is defined as the harvested yield of a high producing variety that is well adapted to the given growing environment, under conditions where water, nutrients, pests and diseases do not limit yield. These methods (Doorenbos and Pruitt, 1977; and Doorenbos and Kassam, 1979) have been used in many regions throughout the world for irrigation planning and management.

Bartholic et al. (1983) used the Doorenbos and Pruitt (1977) method to assess the water requirements of major field crops grown in Michigan. Terjung et al. (1984) modified the method of Doorenbos and Pruitt (1977) to estimate the water requirements of rainfed and irrigated winter wheat in China. However, these two models (Doorenbos and Pruitt, 1977; Doorenbos and Kassam, 1979) do not take into account the effect of crop genetics and management practices, such as plant population and fertilization levels, on the evapotranspiration rate of crops.

Furthermore, the models do not differentiate the effects of soil profile characteristics such as soil texture, porosity, thickness of the soil layer, and organic matter content on evapotranspiration rates at the soil association level. In addition, these models require intensive climatic data, including air and surface temperature, wind velocity, and net radiation. In some locations, data concerning wind velocity and surface temperature are often not available. In these cases, the applicability of the models is limited.

Ritchie et al. (1989) developed a computer simulation model, CERES-MAIZE. The model simulates the effects of particular cultivars, planting density, weather, soil water, and nitrogen on the growth, development, and yield of corn. It takes into account phenological development, extension growth (of leaves, stems, and roots), biomass accumulation and partitioning, soil water balance and water use by the crop. It also takes into account soil nitrogen transformations, uptake by the crop, and partitioning among plant parts in simulating maize growth and yield. The model uses readily available data sets of precipitation and air temperature, soil characteristics, and management practices to estimate potential and actual crop evapotranspiration rates. In computing the soil water balance, the model incorporates the effects of precipitation, runoff, infiltration, drainage, crop developmental stages and irrigation efficiency[9] on irrigation amounts. Outputs of the model include the corn evapotranspiration rate, irrigation dates and amounts, and yield. Similar simulation models were developed for other crops, such as SOYGRO for soybeans (Jones et al., 1989) and BEANGRO for dry beans (Hoogenboom et al., 1990). These models have been tested and used in many areas of the U.S. and other countries, and in numerous instances satisfactory results have been obtained (Jones and Kiniry, 1986).

These simulation models can be used to estimate irrigation water requirements and to develop management decisions in large areas. He et al. (1990) obtained satisfactory results when using the CERES-MAIZE model to estimate the yield and irrigation water requirements of corn on a 30-year basis in the Cass River Watershed of Michigan.

In this study, the simulation models -- CERES-Maize, SOYGRO, and BEANGRO -- are used at the soil association level to estimate the irrigation water requirements and yields of corn, soybeans, and dry beans in the study area. In addition, the FAO YIELD model (Doorenbos and Kassam, 1979) is used to estimate the irrigation water requirements and yield of sugarbeets in the study area.

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[9]Irrigation efficiency is the ratio of average depth of water which is used to satisfy soil moisture demands to the depth of applied water.

2. ESTIMATING GROUNDWATER RECHARGE

Recharge[10] and discharge rates of groundwater are essential knowledge for achieving sustainable use of groundwater resources. Under natural conditions, recharge is balanced by discharge from the aquifer, and the effects of groundwater development are superimposed upon these conditions. The magnitude of sustained groundwater development generally depends on how much of the natural discharge can be captured by the cone of depression[11] (Bredehoeft et al., 1982). Assuming an equilibrium condition between recharge and discharge, changes in groundwater recharge and discharge rates can be used to indicate how much water might be pumped before the aquifer system reaches a new steady state.

Many methods are available to estimate groundwater recharge. Walton (1970) stated that, for a given period of time, precipitation reaching the water table (groundwater recharge) is balanced by groundwater runoff, underflow, and evapotranspiration, plus or minus changes in groundwater

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[10]Recharge is the process by which water infiltrates the unsaturated zone and is added to the zone of saturation. It is also the quantity of water added to the zone of saturation. Major sources of recharge to drift aquifers include infiltration of precipitation, natural or induced infiltration from surface water, and upward leakage from underlying till or bedrock.

[11]The cone of depression is the cone-shaped geometric solid formed, after a well has begun discharging, between the water table (or other potentiometric surface) and the original position of the water table (Morrissey, 1989).

storage. This balance can be expressed as a groundwater budget:

$$P_g = R_g + ET_g + U \pm \Delta S_g$$

where P_g is groundwater recharge, R_g is groundwater runoff, ET_g is groundwater evapotranspiration, U is subsurface underflow, and ΔS_g is change in groundwater storage. Groundwater runoff may be estimated by separating the streamflow hydrograph[12] into surface runoff and groundwater runoff. Groundwater evapotranspiration can be estimated from rating curves[13] of mean groundwater stage versus groundwater runoff. The difference in groundwater runoff between the curve for the period April through October and the curve for the period November through March is the approximate groundwater evapotranspiration. Subsurface underflow can be estimated from Darcy's equation[14]. Changes in groundwater storage can be estimated by the change in the mean water table during an inventory period.

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[12]A streamflow hydrograph is a graph or table showing the flow rate as a function of time at a given location on the stream.

[13]The rating curve is developed using a set of measurements of groundwater discharge and water table height in a well over a period of months or years so as to obtain a relationship between the groundwater discharge and the gage height in the gaging well.

[14]Darcy's equation is: Q=KAI, where Q is the quantity of water per unit of time; K is the hydraulic conductivity; A is the cross-sectional area, at a right angle to the flow direction, through which the flow occurs; and I is the hydraulic gradient.

Allen et al. (1973) evaluated the availability of groundwater in Kalamazoo County, Michigan. Using a groundwater budget similar to Walton's, they estimated that the mean annual groundwater recharge in the Kalamazoo River basin during the 34-year period (1933-66) was about 9 inches. Groundwater runoff contributed about 65 to 80 percent of the stream's total flow.

The relationships between groundwater and surface water were discussed by Pettyjohn and Henning (1979). They pointed out that, over a long period of time, the average annual groundwater runoff is equal to the effective recharge[15] to the aquifer.[16] Therefore, the replenishment of groundwater in a river basin can be estimated by determining the groundwater component of runoff by stream hydrograph separation. Pettyjohn and Henning (1979) considered the effect of geologic framework on groundwater runoff and developed a computer model to estimate groundwater runoff by hydrograph separation. They ran the computer program for a number of river basins in Ohio and demonstrated that groundwater runoff contributed approximately 30 to 51 percent of the total streamflow in the study area.

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[15]Effective groundwater recharge is defined as the total quantity of water that originates from downward infiltration to the water table and upward leakage from deeper zones to the surficial aquifer and eventually reaches a nearby stream. The volume of effective recharge is smaller than the total annual quantity of recharge due to evapotranspiration.

[16]An aquifer is a saturated permeable geologic unit that can yield water in a usable quantity to wells and springs.

Petrie (1984) used different methods of hydrograph separation described by Pettyjohn and Henning (1979) and flow duration ratios ($Q_{10/90}=(Q_{10}/Q_{90})^{1/2}$ and $Q_{25/75}=(Q_{25}/Q_{75})^{1/2}$, where Q_{10}, Q_{25}, Q_{75} and Q_{90} are the discharges equalled or exceeded 10, 25, 75 and 90 percent of the time, respectively), to estimate the recharge of the aquifer system of Michigan's Upper Grand River Basin. The resulting annual recharge values range from 3.95 to 5.5 inches for a water year of almost normal precipitation, and from 2.10 to 8.32 inches for yearly extremes.

Dugan and Peckenpaugh (1985) examined the climate, vegetation, and soil factors that affect consumptive water use and recharge to the groundwater system. They developed a soil-moisture computer program to estimate the recharge to the Central Midwest regional aquifer system. Their equation for computing groundwater recharge was stated as follows:

$$R = (S + P - O - E) - C$$

where R is recharge (deep percolation), S is antecedent soil moisture, P is precipitation, O is surface runoff, E is actual evapotranspiration (AET), and C is moisture storage capacity of the soil zone. Their results demonstrated that mean annual recharge averaged slightly more than 4.5 inches for the entire study area, although the results ranged from less than 0.10 inch in eastern Colorado to slightly more than 15 inches in Arkansas. Patterns of annual recharge closely paralleled yearly and cool season precipitation

(October through March). They concluded that climatic effects dominate overall regional recharge patterns in the study area, and that local variations result from differences in vegetation and soil.

Sophocleous and McAllister (1987) developed a detailed but simple hydrologic budget to characterize the spatial distribution of the hydrologic components of the water balance for the entire Rattlesnake Creek Basin in south-central Kansas. The hydrologic balance equation that they used is :

$$DR = PCP + SD - AE - RO$$

where DR is deep drainage, PCP is precipitation, SD is soil moisture deficit, AE is actual evapotranspiration, and RO is surface runoff. By using minimal daily weather input data and the soil-plant-water system analysis methodology, they showed that, in addition to climatic controls, soil, vegetation, and land use factors also exert a considerable influence on the water balance of the study area. Precipitation is the principal natural water supply, while evapotranspiration is the major water depletion process. The available water capacity of soil profiles plays a dominant role in soil water deficit development and deep drainage (potential groundwater recharge). Vegetation and dryland or irrigated farming particularly affect the evapotranspiration (ET) components, with ET from irrigated corn and alfalfa being two to three times that from wheat. Deep drainage from irrigated wheat fields was significantly higher than that from grassland and dryland wheat, while deep drainage from alfalfa is practically non-existent.

In evaluating the effects of irrigation withdrawal on streamflow reduction, Wallace et al. (1987b) estimated recharge for a surface aquifer in southeastern Michigan using a water budget approach. While assuming negligible movement of water across the lateral and lower boundary of the aquifer, the recharge rate was estimated by the following equation:

$$R = D_e + D_s + \Delta S$$

Where R is the recharge from infiltration and surface water bodies, D_e is the discharge by evapotranspiration, D_s is the discharge to surface water bodies, and ΔS is the change in groundwater storage. The results indicate that the annual net recharge ($R_n = R - D_e$) rate ranged from 4.8 to 9.5 inches during the period from 1971 to 1976. During the summer months of June through August, virtually no infiltrated water reached the water table. If aquifer withdrawal for irrigation had continued for a period of time, groundwater discharge to the stream would have been reduced. The full effect of aquifer withdrawal on reduction in streamflow may not show up for many years.

Groundwater recharge in this study is estimated using a hydrologic budget approach[17], while taking into account the effects of soils, land use, crop characteristics and management practices on evapotranspiration rates of crops. Surface runoff is estimated by separating the streamflow hydrograph into surface runoff and groundwater runoff using a hydrograph separation method described by Freeze and Cherry (1979) and a computer program by Pettyjohn and Henning (1979). Evapotranspiration rates for corn, soybeans, dry beans, and sugarbeets are estimated by the computer simulations models, CERES-MAIZE, SOYGRO, BEANGRO, and YIELD.

The major advantages of the hydrologic budget approach used in this study are: (1) ease of use, (2) minimal data requirements with respect to climate, soils, and the management of crops, and (3) incorporation of the effects of climate, soils, crops, and management factors on groundwater recharge (via estimation of evapotranspiration rates).

3. EVALUATION OF STREAMFLOW CAPACITY

Evaluation of streamflow capacity must consider quantity, variability, and quality of streamflow over a period of time. In humid regions, problems associated with water quantity are often caused by the variability of flow

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[17]Hydrologic budget equation and water balance equation are identical concept and are used inter-changeable in this work.

rather than by the lack of water. The variability of flow in a watershed can be reflected to some degree by minimum, mean, median, and maximum flows over a month or year. However, to best characterize the variability of flow, probability (i.e. the likelihood of a particular flow event) must be used. For irrigation planning, which requires adequate water supply during the irrigation season, the duration of low flows in the driest season (the percentage of time that a flow rate is equaled or exceeded) is the governing factor. Wallace and Annable (1987a) used the August Drought Flow, the discharge that was equaled or exceeded 95 percent of the time in August, to evaluate the availability of surface waters in Michigan.

Wallace (1984) used a water budget approach to evaluate the impact of withdrawing streamflow for agricultural irrigation in Fish Creek in south central Michigan. July exceedence flows of 50 and 90 percent were used to compute the streamflow reduction caused by irrigation. The results indicate that, if all the irrigable land were irrigated by streamflow, July streamflow reduction would range from 50 to 80 percent, and zero flows would occur about 10 percent of the time.

A study by Fulcher et al. (1986) illustrated that the July drought flows at 50 and 95 percent exceedence levels were reduced by 30 to 84 percent due to the consumptive water uses along the River Raisin in southeastern Michigan.

They recommended that the drought flows used in the National Pollutant Discharge Elimination System[18] (NPDES) be reduced to reflect consumptive water uses, and that current waste load allocations be re-evaluated in the watershed.

In a similar study, Wallace et al. (1987b) evaluated the impacts of agricultural irrigation on streamflow in southeastern Michigan. They indicated that if all the currently irrigated land were irrigated by streamflow, the stream would be reduced to zero flow in 4 out of 6 years, for periods of time lasting as long as two months. If the stream was used to irrigate a portion of the irrigated land, flow in the river would be reduced below the 95 percent August low flow. If the flow drops below this level, there is increased risk that the water quality would become unacceptable.

This study assumes that streamflow available for irrigation withdrawal is the amount of water above the 95 percent exceedence flow level set by the National Pollutant Discharge Elimination System (NPDES). The 95 percent exceedence flow is used here as the lower threshold for the purpose of estimating the amount of water for irrigation.

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[18]The NPDES permit process controls the discharge of pollutants into surface waters by imposing effluent limitations to protect the environment. Monthly 95% exceedence flow is used in setting effluent limits. If the discharge of effluents to surface water exceeds the NPDES limit, there is increased risk that the quality of water would be degraded. The lower the value of the 95% exceedence flow in a stream, the less the amount of pollutants that can be discharged into the stream.

The 90, 75, and 50 percent exceedence flows in the irrigation season are used as the upper threshold for computing the maximum irrigation acreage that streamflow can support without degrading water quality.

4. USE OF OPTIMIZATION TECHNIQUES FOR WATER RESOURCE MANAGEMENT

Optimization techniques have been used in many studies of water resource management, either to attain a maximum (minimum) objective function with the given resources, or to meet the given goal with a minimum of resources. Gisser (1970) applied parametric linear programming methods to estimate the agricultural production function for imported irrigation water for corn, barley, sorghum, and alfalfa in the Pecos River Basin, New Mexico. The study showed the expected quantities of imported irrigation water that would be demanded at different prices and under a variety of constraints. Gisser et al. (1979) developed linear programming models to estimate the impact of shifting water from agriculture to the electric generating sector on the regional income of New Mexico. A study by Bras and Cordova (1981) optimized the temporal allocation of irrigation water for corn while taking into consideration the intraseasonal stochastic variation of the crop water requirements and the dynamics of the soil moisture depletion process. Bredehoeft and Young (1983) coupled a stream aquifer simulation model to a linear programming model to optimize the groundwater pumping capacity for irrigating all the available acreage of crop land in the South Platte Valley of Colorado. They concluded that under the given economic conditions in the South Platte Valley of Colorado, the most reasonable groundwater capacity would be a total capacity capable of irrigating the entire 65,500 acres of crop land with groundwater. Installing sufficient pumping capacity to totally discount surface water for irrigating all available acreage would maximize the expected net benefit and minimize the variance in expected income.

Schmidt and Plate (1983) developed a stochastic optimization model to optimize the size of the irrigation area and the operation schedule of a reservoir delivering irrigation water for maximizing the crop production return in the Arabian Peninsula. They concluded that, with all of the water available in the Peninsula, the optimal irrigation design area was 1,500 hectares (3,675 acres). Singh et al. (1987) used linear and goal programming models to optimize the irrigation water supply for winter crops such as wheat, oilseeds and potatoes in Assam, India, while meeting the constraints of land, water, and protein requirements. Ponnambalam and Adams (1987) used a stochastic dynamic programming model to optimize the reservoir water supply for irrigation in India. Based on a single crop irrigation scheduling model, Rao et al. (1990) developed linear programming and dynamic programming models to generate optimal weekly irrigation schedules of sorghum and cotton in India. These optimization studies considered the average economic coefficients (average gross income or net income per unit of land), crop areas, and crop growth stages to some degree. However, the effects of soil variations on crop irrigation requirements and yields were not considered in these studies.

This study attempts to optimize the mix of multiple crops (i.e. corn, dry beans, soybeans, and sugarbeets) in the Cass River Watershed of the Saginaw Bay area to maximize the expected returns of irrigation. Simulation models of corn, dry beans, soybeans, and sugarbeets, and streamflow supply equations are integrated with linear programming models to optimize the expected irrigation returns under different water supply conditions. Effects of soil characteristics, climate, crop growth stages and genotypes, management practices such as fertilization and plant population, and crop budgets on irrigation water requirements and crop yields are considered over a 30-year period at the soil association level. In computing the economic coefficient (the expected gross margins per acre of land) for each of the four crops, the seasonal average value and 25th percentile[19] value of crop prices are used in the

[19]The 25th percentile value of crop prices indicates that crop prices in a particular year will be greater than the specified price 75 percent of the time.

study to avoid the overstatement of the expected returns of the optimal crop mix.

5. USE OF GEOGRAPHIC INFORMATION SYSTEMS IN WATER RESOURCE MANAGEMENT

A Geographic Information System (GIS) is a system of computer hardware, software, and procedures designed to support the capture, management, manipulation, analysis, medullary and display of spatially referenced data for solving complex planning and management problems (Antenucci et al., 1991). In recent years, GIS has been used more widely to improve water resource management. Many government agencies (e.g., U.S. Army Corps of Engineers, Oak Ridge National Laboratory, Tennessee Valley Authority, and agencies in Colorado, Maryland, Michigan, Minnesota, Nebraska, North Carolina, Pennsylvania, and Texas) have been using GIS in water resource management and planning (Lindhult et al., 1988). Applications include mapping land use/land cover, delineating watershed boundaries, conducting soil surveys and stream and lake inventories, monitoring and remediating surface water and groundwater contamination, evaluating water supplies, and analyzing water use impacts.

GIS is also used in modeling activities. Soloman et al. (1968) used a grid system to estimate precipitation, temperature, and runoff in a 43,000 square mile area. Based on soil and agricultural capability survey data, Nagpal et al. (1986) mapped irrigation water requirements using a vector GIS and water requirement model in Vancouver Island, British Columbia. He et al. (1987) integrated a raster GIS and remote sensing data with evapotranspiration models to evaluate the impacts of human activity on changes in the surface conditions of the earth. Harris et al. (1989) combined a vector GIS with a three-dimensional finite element model to simulate groundwater flow in San Gabriel Basin, California. GIS was used in their study to process and manage the hydrogeologic data sets, to provide the input parameters to the finite element model, and to display the simulated results. Hamlett and Petersen (1992) incorporated data sets of watershed boundaries, land use, animal density, topography, soils, precipitation, and rainfall-runoff factors into a GIS-modeling system to rank the agricultural nonpoint pollution potential of 104 watersheds in Pennsylvania.

In this study, GIS is used to store, process, and analyze the data sets of land use, soil associations, watershed boundaries, well log records, and geology to provide input parameters to the simulation and optimization models as well as the water balance equation for estimating irrigation requirements, evaluating the availability of groundwater and streamflow for irrigation, and developing optimal crop mixes. Simulated results are processed and displayed using GIS at the watershed scale.

CHAPTER 4

PHYSICAL AND SOCIO-ECONOMIC CONTEXT OF IRRIGATION DEVELOPMENT IN THE SAGINAW BAY AREA

1. CLIMATE

Michigan is located in the heart of the Great Lakes region and consists of two large peninsulas. The lower peninsula comprises approximately 70 percent of Michigan's total land area. It extends northward nearly 300 miles from the Indiana-Ohio border (42°N latitude) to the Straits of Mackinac (46°N latitude).

The Great Lakes surround Michigan and strongly influence the state's climate. For example, the lake waters' slow response to temperature changes and the dominating westerly winds retard the arrival of both summer and winter. In the spring, cool temperatures within a few miles of the shoreline slow the development of vegetation and reduce the danger of frost. In the fall, warm lake waters temper the first outbreaks of cold air and allow additional time for crops to mature or reach a stage less vulnerable to frost damage (Nurnberger, 1985).

The Saginaw Bay Watershed is located in the east central portion of the lower peninsula and is surrounded by the Saginaw Bay of Lake Huron in the east. The mean annual temperature in the study area ranges between 46 - 47 °F. Due to the close proximity of the lake, the latitude and the local topography, the growing season[20] ranges from 154 days in Saginaw County (Saginaw Consumer Power station), to 147 days in Sanilac County (Sandusky station), 144 days in Huron County (Bad Axe station), and 122 days in Tuscola County (Caro station). The seasonal (March - October) growing degree days from 1951-1980 averaged between 2,382 and 2,758 °F (see Table 1)[21].

Table 1. Growing season length, temperature, and precipitation in the Saginaw Bay Area (1951-1980)

Station	Growing Season (Days)	Annual Mean T. (°F)	Degree days-50 (°F)	Annual Precip. (inches)	Seasonal Precip. (Apr-Sep)
Bad Axe	144	46.0	2,382.4	29.35	16.74
Caro	122	46.8	2,556.0	28.22	17.02
Saginaw C.P.	154	47.7	2,758.1	28.95	17.44
Sandusky	147	46.7	2,496.9	27.96	16.47

Source: Michigan Department of Agriculture Climatology Program.

Annual mean precipitation in the study area ranges between 28 and 29 inches. While there are no pronounced wet or dry periods, the mean precipitation during the growing

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[20]The growing season is defined as the number of days between the last spring 32°F on or before July 31 and the first fall 32°F temperature after July 31.

[21]The growing degree day is the average daily temperature above a selected base temperature. The base temperature used here is 50 °F.

season (April - September) is between 16 and 17 inches and accounts for about 60 percent of the annual total precipitation. The monthly distribution of precipitation is shown in Figure 5.

2. CROP MIX IN THE STUDY AREA

The Saginaw Bay area comprises one of the most productive farmlands in Michigan. The production of field crops for food and livestock feed plays a leading role in the region's economy. Major field crops in the study area include corn, soybeans, dry beans, and sugarbeets. Production of these crops in the study area accounted for 20.1, 23.7, 63.6, and 80.8 percent, respectively, of the total production in the State of Michigan in 1989 (Michigan Department of Agriculture, 1990). The harvested acreage of the four crops collectively accounted for 80 percent of the total harvested crop acreage in the five county area (Bay, Huron, Saginaw, Sanilac, and Tuscola). Percentage of harvested acreage of the four crops to the total harvested crop acreage over the period from 1959-1988 is shown in Figure 6. Of the five counties in the study area, Huron County is ranked first in the state in the production of corn, dry beans and barley, Saginaw County is ranked first in the state in soybean production, and Sanilac County is ranked first in the state in the production of wheat and oats.

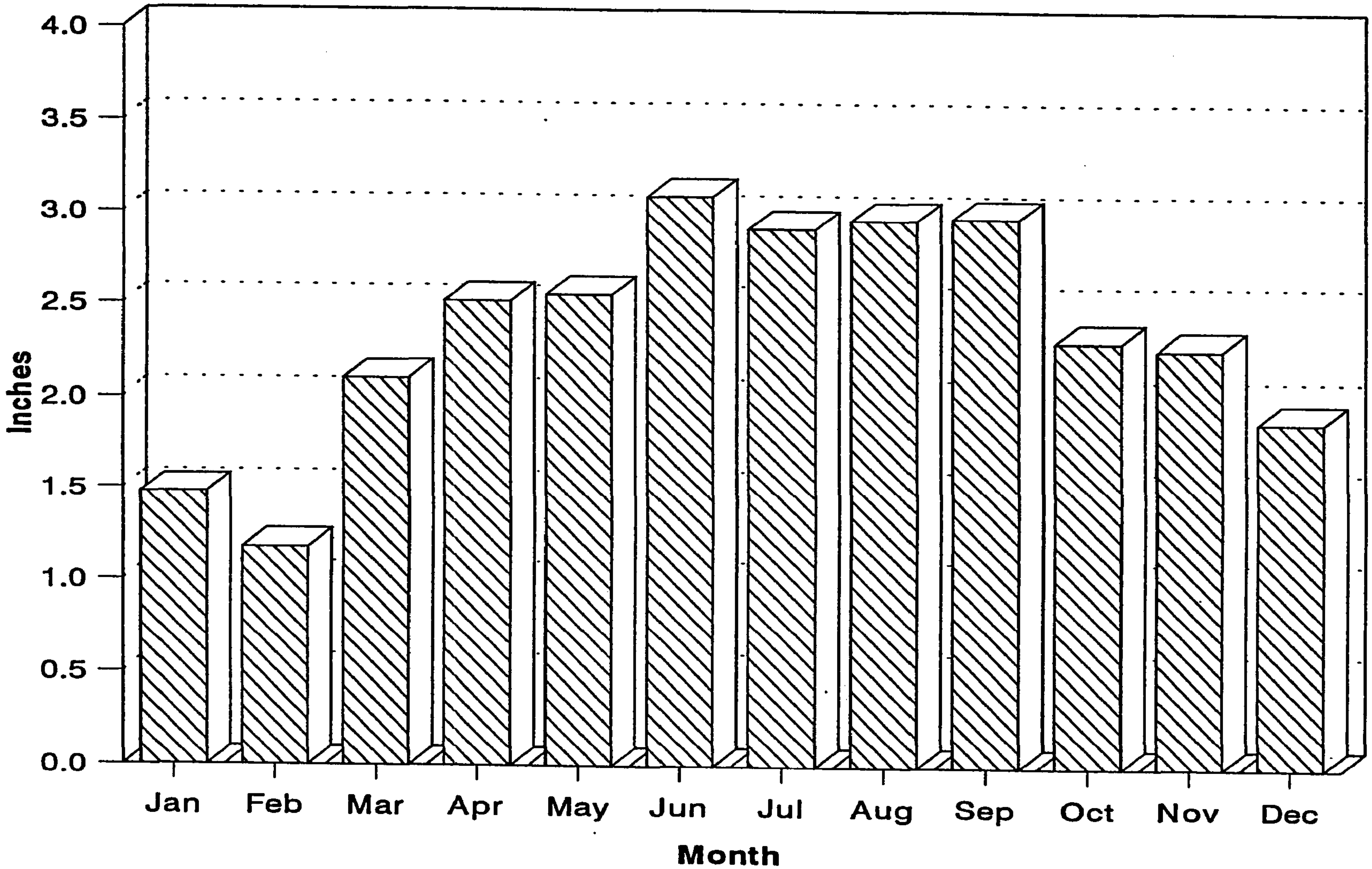

Figure 5. Mean Monthly Precipitation (inches) in Caro, Michigan (1951-1980)

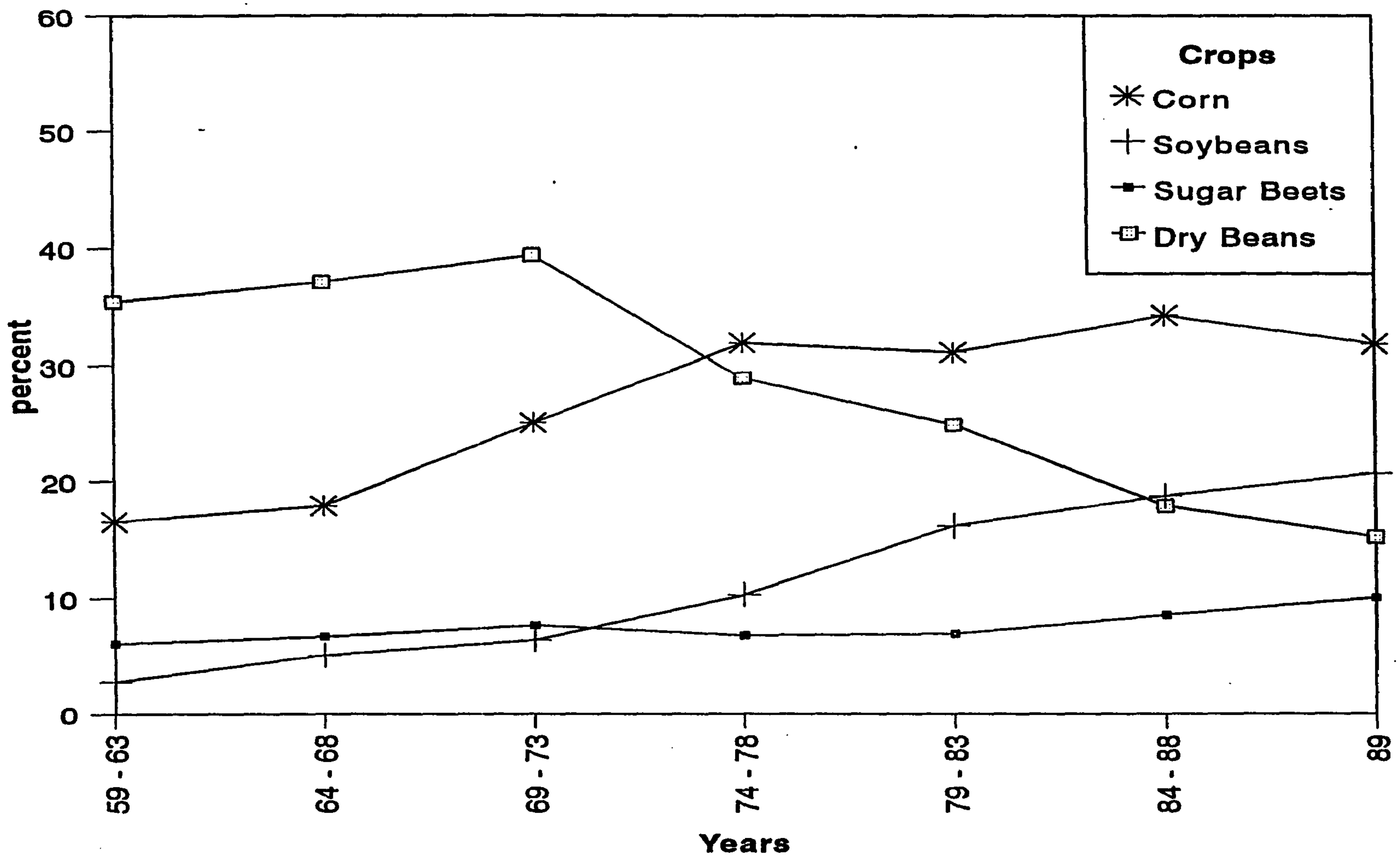

Figure 6. Harvested Acreage of Corn, Soybeans, Sugar Beets, and Dry Beans as a Percentage of the Total Crop Acreage Harvested in the Five County Area (Based on Five Year Intervals)

As seen in Figure 6, there have been some changes in the crop mix between the periods of 1959-63 and 1984-88. The percentage share of corn and soybeans compared to the total harvested acreage of field crops increased from 16.5 and 2.8 percent during 1959-1963 to 34.3 and 18.7 percent, respectively, during 1984-1988. During the same period, the percentage of sugarbeets was relatively stable. However, the percentage acreage share of dry beans decreased from 35.5 to 17.9 percent. These changes may be due to: (1) progress in crop breeding and the management of high yield corn and soybean cultivars that have been bred to adapt to the climate of the Saginaw Bay Watershed in areas where they would not have been grown during the 1960's; (2) compared to corn and soybeans, dry bean production is labor intensive; (3) the rotation of corn and soybeans improves yield and soil organic matter content; and (4) the production of sugarbeets is limited by the sugar processing capacity of the companies that manufacture sugar (Michigan Department of Agriculture, 1959-1990; Christenson, 1991; LeCureux, 1992; and Rouget, 1992, personal communication).

3. CROP YIELD VARIABILITY

The average yields of the four crops grown in the five county area between 1959 and 1989 are: 85.3 bushels per acre (5,346 kg/ha) for corn, 24.6 bushels per acre (1,654 kg/ha) for soybeans, 12.0 cwt (hundred weight) per acre (220 kg/ha) for dry beans, and 17.7 short tons[22] per acre (39,678 kg/ha) for sugarbeets (Table 2). The coefficients of variation[23] for the four crops over the period 1959-1989 are: 0.198 for corn, 0.253 for soybeans, 0.146 for dry beans, and 0.112 for sugarbeets. A comparison of these coefficients indicates that dry beans and sugarbeets had relatively stable yields during the period of 1959-1989 while the yield variations of corn and soybeans were relatively greater.

Table 2. Average Crop Yields and Coefficient of Variation over the Period 1959-1989

Period	Corn (bu/a)	Soybean (bu/a)	Drybean (cwt/a)	Sugarbeet (ton/a)
1959-1989	85.3	24.6	12.0	17.7
Coef. Var.	0.198	0.253	0.146	0.112

Source: Michigan Agricultural Statistics, 1959-1990.

The variations in the production of corn, soybeans, dry beans, and sugarbeets were affected by multiple factors including weather, soils, and management practices. Correlation analysis between the crop climatic yields[24] and the monthly mean precipitation and temperature reveals that

[22] 1 short ton = 2,000 lbs

[23] The coefficient of variation is the ratio of standard deviation to the mean of the sample. It measures the relative magnitude of variation.

[24] Crop climatic yield is defined here as the difference between the actual yield and the three year moving average yield. The assumption was that technology would remain the same during a three-year period and the changes in crop yield during this period were caused by fluctuation of climate.

the production of corn was positively related to the amount of precipitation during June through August. Soybean production was positively related to the July mean temperature and the amount of precipitation during July through August. The production of dry beans was inversely related to the mean temperatures between May and June (see Table 3).

Table 3. Correlation Coefficients between Crop Climatic Yields and Precipitation and Temperature.

Crop	Precipitation		Temperature	
	Period	r	Period	r
Corn	Jun. - Aug.	0.648 **		
Soybeans	Jul. - Aug.	0.612 **	July	0.442*
Drybeans			May - June	-0.489*

Note: Crop yields of Tuscola County and weather data (1951-1980) from the Caro Station were used in this analysis.

The correlation analysis indicates that the period from June through August is a critical period for managing corn and soybean production (grain forming and filling period). Irrigation may be needed during this period to ensure an adequate water supply for plant growth. Similarly, drybeans are sensitive to the mean temperature during May and June, and appropriate planting dates should be determined to ensure that adequate yields are obtained.

4. SOIL SUITABILITY FOR IRRIGATION EXPANSION

The soils in the Saginaw Bay area are mainly loamy and silty clays on nearly level to gently sloping topography, and are poorly drained in much of the area. They have moderate to high available water capacity and slow to very slow permeability (Michigan State University, 1981). A compact layer is present within 6 feet of the surface in a majority of the area. Based on soil properties (which include slope, texture, permeability, and natural drainage), Kittleson et al. (1987) evaluated the suitability of soils for subsurface irrigation in the Saginaw Bay area. The most important factors used in classifying the suitability of soils for subsurface irrigation were the presence or absence of a barrier layer within 6 feet of the surface as well as the drainage and slope characteristics of the soil. First, if a barrier layer with low permeability (less than 0.02 inch/hr) is present between 40 - 60 inches of the surface in a very flat (slope less than 1%) and poorly drained soil association, this association was believed to be highly suitable for subsurface irrigation. Second, soil associations which have a moderately low permeability (between 0.02 and 0.06 inch/hr) layer within 40-60 inches of the surface and are both flat (slope between 1 - 2 %) and moderately well drained were classified as less suitable (i.e. medium suitability) for subsurface irrigation. Third, associations which are well drained and have a layer with a permeability greater than 0.06 inch/hr which lies between 40 and 60 inches of the surface were grouped as not suitable for subsurface irrigation. Considering all of the factors (which include presence of a barrier layer within 40-60 inches of surface, slope, texture, and natural drainage characteristics), Kittleson et al. (1987) derived a soil suitability map for subsurface irrigation in the Saginaw Bay area. Their results indicate that 85 percent (1,667,000 acres) of the total agricultural land in the study area would be suitable for subsurface irrigation (see Table 4 and Figure 7). Thus, there is a great potential for subsurface irrigation expansion in the Saginaw Bay area.

Table 4. Agricultural Land Soil Suitability for Subsurface Irrigation in the Saginaw Bay Area

Soil Suitability	Acres	%
Highly Suitable	437,582	22.2
Less Suitable (Medium)	1,229,414	62.3
Not Suitable (Low)	304,937	15.5
Total	1,971,933	100.0

In summary, annual mean temperature and precipitation in the Saginaw Bay area average around 47 °F and 29 inches, respectively. The four major field crops in the region are corn (34.3 percent of the total harvested acreage of all field crops), soybeans (18.7 percent), dry beans (17.9 percent), and sugarbeets (8.6 percent). These crops

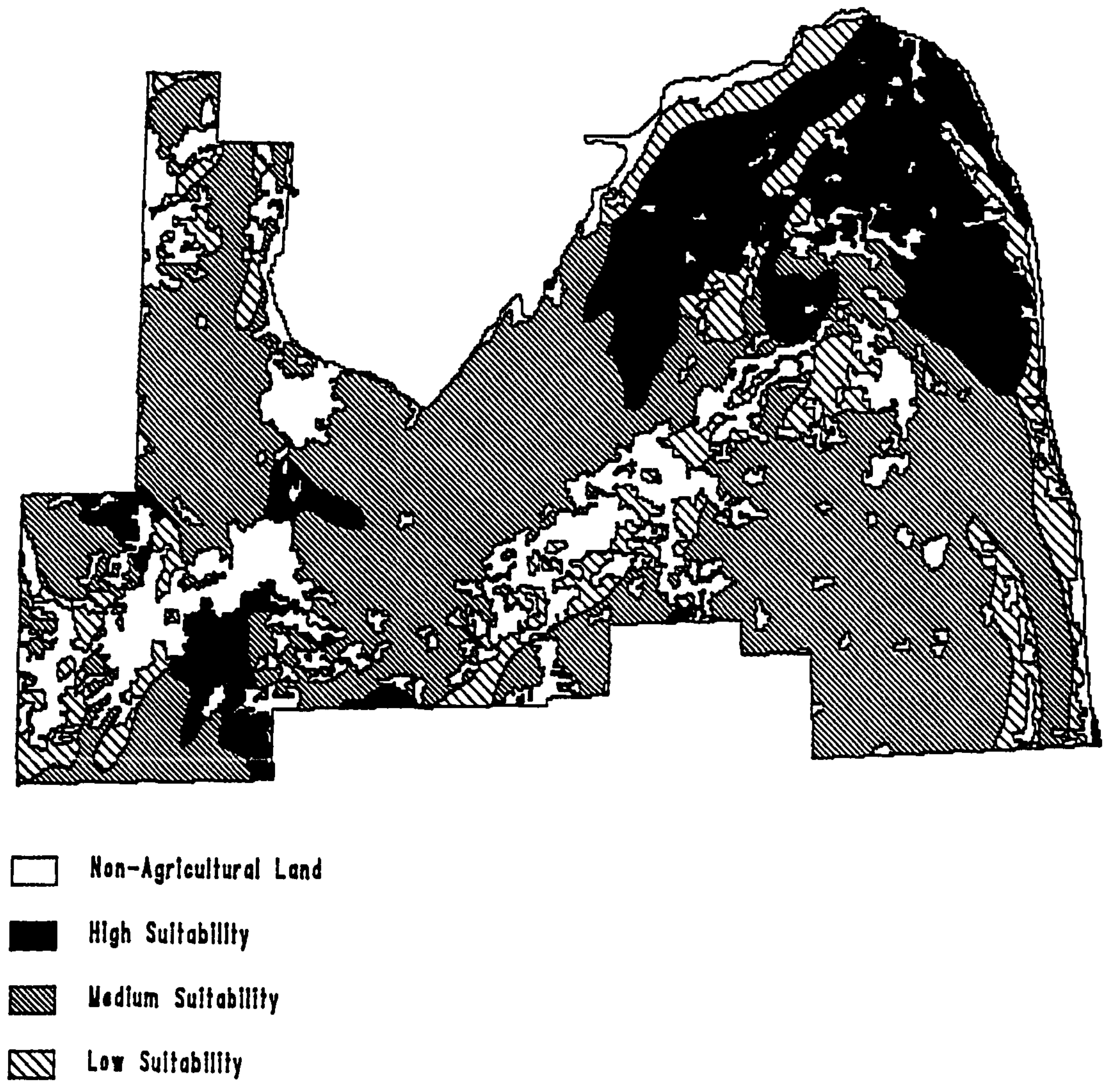

Figure 7. Soil Suitability for Subsurface Irrigation

collectively account for about 80 percent of the total harvested crop acreage. The production of corn and soybeans are positively related to the amount of precipitation during the period from June through August. Appropriate crop management during this period is critical. Based on the suitability of soils, the potential exists for as many as 1,667,000 acres of subsurface irrigation expansion in the Saginaw Bay area.

CHAPTER 5

MASS BALANCE OF IRRIGATION WATER REQUIREMENTS AND AVAILABLE WATER RESOURCES

Streamflow and groundwater are used for agricultural irrigation and domestic uses in parts of the Saginaw Bay area. The currently irrigated crop land in the Saginaw Bay five-county area[25] is 15,035 acres (Bureau of the Census, 1989). However, the potential exists to irrigate as many as 1.67 million acres using subsurface irrigation based on the suitability of soils. To assure an adequate water supply for the potential expansion of irrigation, the irrigation requirements and the availability of groundwater and streamflow must be evaluated before large investment is committed to irrigation expansion.

I. CROP IRRIGATION WATER REQUIREMENTS

The irrigation water requirement of a crop is the difference between its water need and available soil moisture and effective precipitation[26] (Bartholic et al.,

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[25]The Saginaw Bay five-county area refers to Bay, Huron, Saginaw, Sanilac and Tuscola counties.

[26]Effective precipitation = total precipitation - surface runoff - deep percolation

1983). In this study, simulation models are used to estimate the irrigation water requirements for corn, soybeans, dry beans and sugarbeets.

1. DESCRIPTION OF THE IRRIGATION SYSTEM

The irrigation system examined in this study is an agricultural crop production system in the Saginaw Bay Watershed, Michigan. The Cass River Watershed, a subwatershed, was chosen as a pilot study area to estimate the crop requirements for irrigation. The watershed runs across Huron, Sanilac, Tuscola, Lapeer, Genesee and Saginaw Counties, and has a drainage area of 841 square miles (Figure 8).

Agriculture, the major land use in the Cass River Watershed, accounts for 67 percent of the total land area (Figure 9). Soils in the watershed consist mainly of loamy and silty clays and sands, and are poorly drained in much of the area. The spatial distribution of 12 soil associations in the Cass River Watershed is shown in Figure 10 and Table 5. The predominant associations are Marlette-Capac, Capac-Parkhill, Pipestone-Kingsville-Saugatuck-Wixom, Metamora-Blount-Pewamo, and Boyer-Wasepi, which collectively account for 77 percent of the total land area.

The four crops being studied are corn, soybeans, dry beans, and sugarbeets. They collectively accounted for approximately 80 percent of the total harvested acreage

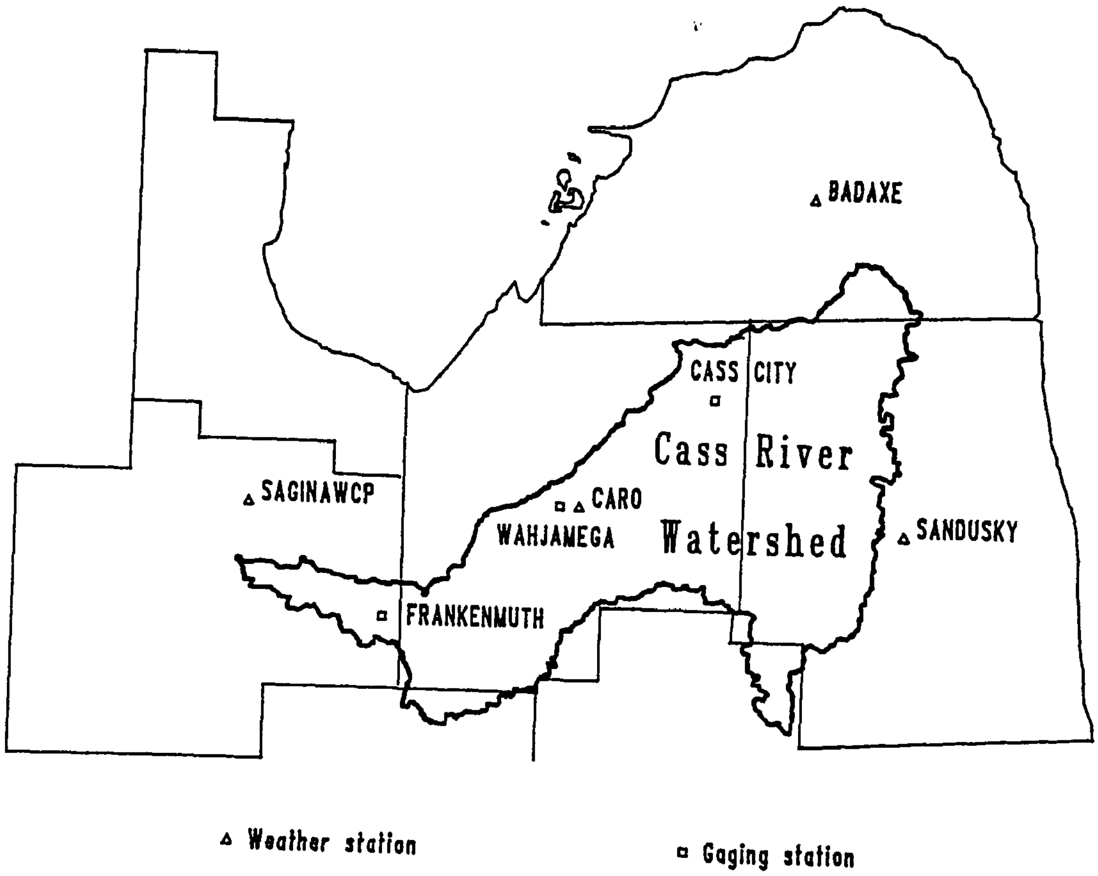

Figure 8. The Cass River Watershed Boundary

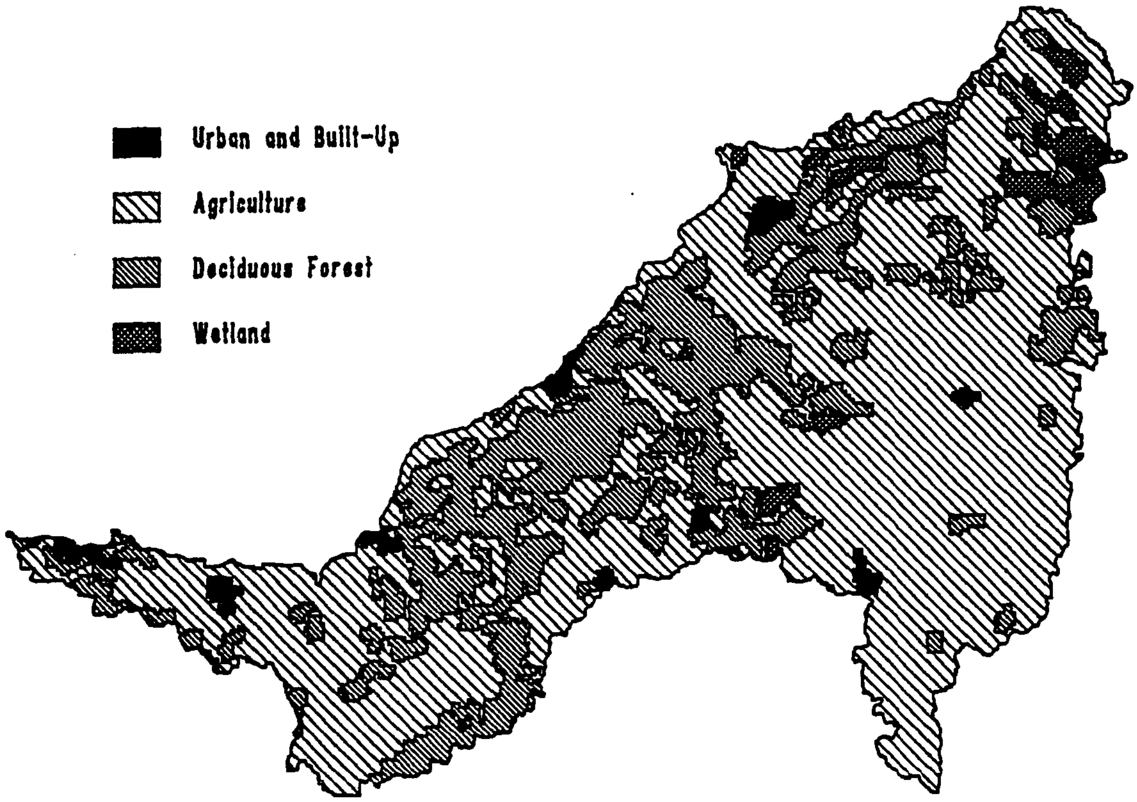

Figure 9. Land Use in the Cass River Watershed

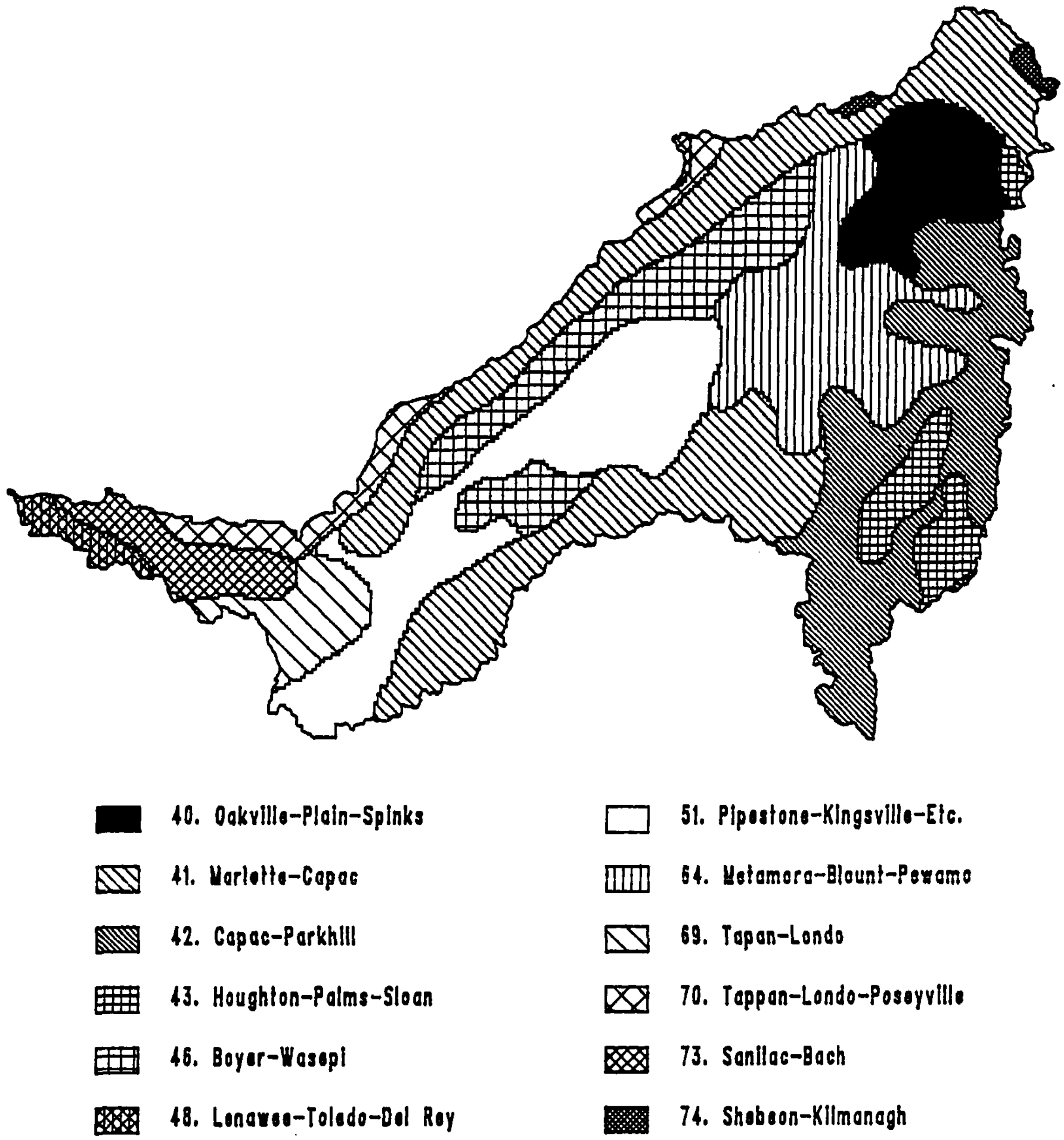

Figure 10. Soil Associations in the Cass River Watershed

between 1985 and 1989 in the Saginaw Bay five-county area (Michigan Department of Agriculture, 1986-1990).

Table 5. Soil Associations in the Cass River Watershed

Soil No.	Soil Association	Acres	%
40	Oakville-Plainfield-Spinks	35,355	6.1
41	Marlette-Capac	153,105	26.3
42	Capac-Parkhill	91,798	15.8
43	Houghton-Palms-Sloan	24,714	4.2
46	Boyer-Wasepi	56,788	9.8
48	Lenawee-Toledo-Del Rey	7,812	1.3
51	Pipestone-Kingsville-Saugatuck-Wixom	76,846	13.2
64	Metamora-Blount-Pewamo	71,671	12.3
69	Tappan-Londo	20,508	3.5
70	Tappan-Londo-Poseyville	19,549	3.4
73	Sanilac-Bach	21,146	3.6
74	Shebeon-Kilmanagh	2,945	0.5
	Total	582,237	100.0

2. SIMULATION OF THE IRRIGATION SYSTEM

2.1 Description of the Simulation Models

The irrigated crop production system in this study consists of three components: the crops, the soil, and the inland water resources. Inputs to the system include precipitation, solar radiation and management practices. Outputs of the system include grains, beets, nutrients and runoff. Computer models are used to simulate the interactions between the three components to estimate evapotranspiration, irrigation water requirements, and the yields of corn, soybeans, dry beans, and sugarbeets. The computer models used include WGEN, CERES-MAIZE, SOYGRO, BEANGRO and YIELD.

WGEN is a weather simulation program developed by Richardson and Wright (1984). It generates solar radiation estimates from precipitation and maximum and minimum temperature data for use in the CERES-MAIZE, SOYGRO, BEANGRO, and YIELD models.

CERES-MAIZE (Ritchie et al., 1989), SOYGRO (Jones et al., 1989), and BEANGRO (Hoogenboom et al., 1990) are crop growth simulation models for corn, soybeans, and dry beans, respectively. They use daily weather data, soil characteristics, and management information to estimate crop yields and irrigation water requirements.

YIELD is a computer model (Schultink et al., 1989) based on a method developed by FAO[27] (Doorenbos and Kassam, 1979) and is used to estimate crop yield, evapotranspiration, and irrigation requirements. The FAO method was modified in the computer model to incorporate slope, soil water content and fertilizer usage information. Inputs to the model include

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[27]This method was developed to estimate the production potential of many crops based mainly on the climatic conditions. It does not take into account the effects of crop genetics, soil profile characteristics, and management practices on evapotranspiration rate and yield.

daily or monthly mean temperature, precipitation, solar radiation, wind speed (at 2 m height), and relative humidity. The YIELD model is used in this study to estimate the yield and irrigation water requirement of sugarbeets.

2.2 Model Inputs and Outputs

A. Climatic Data

Daily minimum and maximum temperature in °F and precipitation in inches are required to run the WGEN and CERES-MAIZE, SOYGRO, and BEANGRO models. Thirty year climatic data (1951-1980) for the Bad Axe, Caro, Flint, Saginaw Consumer Power, and Sandusky weather stations were obtained from the Michigan Department of Agriculture Climatology Program. The locations of these weather stations are shown in Fig. 8. The data sets from these weather stations were entered into the WGEN model to generate solar radiation estimates for use in the simulation models. Monthly mean temperature, precipitation, duration of sunshine (%), wind speed (in m/s at 2 m height) and relative humidity data obtained from the Flint weather station (located in Genesee County, south of the study area) were used in the YIELD model to estimate yield and irrigation requirement of sugarbeets.

B. Soil Data

Soil characteristics data are also required to run the CERES-MAIZE, SOYGRO, and BEANGRO models. The necessary data set includes the following parameters: soil type, classification, bare soil albedo, porosity, SCS runoff curve number, thickness of the soil layer, lower limit of plant extractable soil water, drained upper limit of soil water content, saturated water content, moist bulk density, and organic carbon concentration in the soil layer (Jones and Kiniry, 1986). The soil characteristics for the study area were obtained from the Michigan State University Nowlin Chair's Office and the U.S. Department of Agriculture Soil Conservation Service.

C. Management Information

Management inputs to the simulation models include crop varieties and their genetic coefficient data, planting and harvest dates, plant population, row spacing, and type and amount of fertilizer to be used. Management data in this study were acquired from the Huron County Cooperative Extension Service Office (LeCureux, 1988a, 1988b, 1990a) and the Saginaw Valley Bean and Beet Research Farm (Christenson et al., 1986, 1987, 1988, and 1989).

D. Model Outputs

The model outputs used in this study include crop development stages, leaf area index, ground biomass (g/m^2), root weight (g/plant), root depth (cm) and root length density (cm root/cm^3); organic nitrogen content (kg/ha) and elemental nitrogen as nitrate (NO_3, kg/ha) and ammonium (NH_4) in the soil profile, total nitrification (kg/ha), leaching of nitrate (kg/ha) and total plant nitrogen uptake (kg/ha); cumulative evapotranspiration (ET, mm), precipitation (mm), irrigation water requirements (in mm), irrigation date, plant-extractable soil water in the soil profile (in cm); grain number (grains/m^2), dry single kernel weight (g/kernel), and grain yields (in kg/ha, bu/acre, cwt/acre, or short ton/acre).

3. SIMULATION RESULTS AND DISCUSSION

3.1 Irrigation Water Requirements Per Acre of Land

The irrigation water requirements of corn, soybeans, and dry beans were estimated for 25 to 30 years by performing simulations that rely on data obtained from the weather stations at Bad Axe, Caro, Saginaw Consumer Power, and Sandusky for each of the 12 soil associations in the Cass River Watershed. The locations of these four weather stations and the 12 soil associations were digitized using

C-Map and PC ARC/INFO[28], and are shown in Figures 8 and 10, respectively. The irrigation requirement of sugarbeets was simulated for all soils for 32 years by using the YIELD model based on the weather data from the Flint weather station in Genesee County. Distinctions of irrigation requirements and yields for sugarbeets between soil associations were not made because of limitations in the YIELD model and the lack of wind speed data.

The CERES-MAIZE, SOYGRO, BEANGRO, and YIELD models were run over 2,200 times to estimate irrigation requirements and yields of corn, soybeans, dry beans, and sugarbeets for different soil associations and weather stations. The outputs of these 2,200 simulations are statistically divided into two groups: mean and 25th or 75th percentile. The summary values at the mean level are just simple, arithmetically averaged values. The summary values at the 25th percentile (used for crop yields) indicate that the crop yield in an individual year will be smaller than the specified yield 25 percent of the time, and will exceed or equal the specified yield 75 percent of the time. For irrigation water requirements, the value at the 75th percentile indicates that the requirement for irrigation in

[28]C-MAP is a geographic information system developed at the Michigan State University Center for Remote Sensing, East Lansing, MI. ARC/INFO is a trademark of Environmental Systems Research Institute, Inc., Redlands, CA.

a particular year will be smaller than the specified value 75 percent of the time.[29]

The output summaries of the simulations are listed in Tables 6-9. The irrigation requirements are greatest in July when the four crops are at their critical development stage (silking or blossoming and starting grain filling for corn, dry beans and soybeans, and the rapid development period of roots for sugarbeets) and need adequate soil moisture to obtain high yields. Irrigation requirements at the mean level average 77 mm (3.03 inches) for corn, 105 mm (4.13 inches) for soybeans, 102 mm (4.02 inches) for dry beans, and 69 mm (2.72 inches) for sugarbeets. Irrigation requirements at the 75th percentile average 108 mm (4.25 inches) for corn, 140 mm (5.51 inches) for soybeans, 130 mm (5.12 inches) for dry beans, and 96 mm (3.78 inches) for sugarbeets (Figure 11). Irrigation may increase yields of corn, soybeans, dry beans and sugarbeets by a large margin over non-irrigated identical plantings in the simulated study area (Figure 12).

[29]It is not sufficient to consider how crops respond to the average characteristics of the environmental inputs. The use of statistical values at the 25th or 75th percentile will better represent the historical trends of the crops' responses to the environmental variables and will be less subject to overstatement.

Table 6. Simulated Average Irrigation Water Requirements (mm) at the 75th Percentile

			Corn			Soybean			Drybean			Sugarbeet*		
Location	Period	Soil #	June	July	Aug	June	July	Aug	June	July	Aug	June	July	Aug
Bad Axe	30	40	43	129	86	0	129	132	0	130	90	24	96	71
	30	41	53	107	54	51	156	109	51	145	105	24	96	71
	30	74	54	109	58	46	154	113	0	142	109	24	96	71
Caro	25	41	55	107	55	52	160	107	48	154	104	24	96	71
	25	46	53	106	54	0	142	106	0	143	86	24	96	71
	25	51	38	105	73	34	141	116	35	141	71	24	96	71
	25	70	53	109	105	0	112	109	0	109	56	24	96	71
Sandusky	30	42	0	105	53	0	151	107	0	138	102	24	96	71
	30	43	0	95	97	0	97	97	0	94	93	24	96	71
	30	64	47	98	96	0	142	125	0	145	97	24	96	71
Saginaw	25	48	56	110	57	54	118	111	51	116	57	24	96	71
	25	69	56	110	58	53	159	114	0	114	107	24	96	71
	25	70	54	108	105	0	140	109	0	135	96	24	96	71
	25	73	60	117	60	57	155	117	54	120	60	24	96	71
Mean			44	108	72	25	140	112	17	130	88	24	96	71

* Note: For sugarbeets the values are the same for all soils and all stations due to the limitation of the YIELD model and availability of the weather data.

Table 7. Simulated Average Irrigation Water Requirements (mm) at the Mean Level

			Corn			Soybean			Drybean			Sugarbeet*		
Location	Period	Soil #	June	July	Aug	June	July	Aug	June	July	Aug	June	July	Aug
Bad Axe	30	40	23	96	60	1	92	98	0	105	66	11	69	50
	30	41	30	82	54	17	117	91	16	106	63	11	69	50
	30	74	23	85	53	12	109	95	11	105	58	11	69	50
Caro	25	41	38	82	53	26	123	79	16	110	63	11	69	50
	25	46	33	84	57	0	101	88	0	103	59	11	69	50
	25	51	33	79	58	17	115	91	12	115	56	11	69	50
	25	70	20	83	56	4	108	87	0	103	54	11	69	50
Sandusky	30	42	8	69	50	2	94	92	2	95	58	11	69	50
	30	43	0	37	45	0	60	75	0	51	48	11	69	50
	30	64	19	74	57	0	91	93	0	99	58	11	69	50
Saginaw	25	48	28	70	49	18	107	73	13	104	48	11	69	50
	25	69	28	83	60	13	120	86	7	108	60	11	69	50
	25	70	25	79	60	4	113	89	2	110	53	11	69	50
	25	73	34	75	53	25	116	87	14	113	49	11	69	50
Mean			24	77	55	10	105	87	7	102	57	11	69	50

* Note: For sugarbeets the values are the same for all soils and all stations due to the limitation of the YIELD model and availability of the weather data.

Table 8. Simulated Average Crop Yields at the 25th Percentile

	Location	Period (yrs.)	Soil #	Corn		Soybean		Drybean		Sugarbeet*	
				kg/ha	bu/ac	kg/ha	bu/ac	kg/ha	lbs/ac	kg/ha	tons/ac
Irrigated	Bad Axe	30	40	6437	102.5	2059	30.6	4618	4122.0	67380	27.3
		30	41	7035	112.0	2619	39.0	4756	4245.1	67380	27.3
		30	74	7105	113.1	2627	39.1	4758	4246.5	67380	27.3
	Caro	25	41	10830	172.4	3085	45.9	4543	4054.4	67380	27.3
		25	46	10024	159.6	2289	34.1	4418	3943.2	67380	27.3
		25	51	10100	160.8	2840	42.3	4526	4039.4	67380	27.3
		25	70	11151	177.6	2683	39.9	4432	3956.1	67380	27.3
	Sandusky	30	42	9755	155.3	2661	39.6	4428	3951.8	67380	27.3
		30	43	9823	156.4	3028	45.1	4429	3953.1	67380	27.3
		30	64	9697	154.4	2105	31.3	4361	3892.6	67380	27.3
	Saginaw	25	48	11065	176.2	2729	40.6	4159	3711.7	67380	27.3
		25	69	11060	176.1	2625	39.1	4140	3695.4	67380	27.3
		25	70	11034	175.7	2617	39.0	4030	3597.4	67380	27.3
		25	73	10298	164.0	3089	46.0	4238	3782.4	67380	27.3
	Mean			9672	154.0	2647	39.4	4417	3942.2	67380	27.3
Nonirrigated	Bad Axe	30	40	2713	43.2	400	5.9	621	554.0	58150	23.5
		30	41	3367	53.6	737	11.0	1474	1315.4	58150	23.5
		30	74	3918	62.4	640	9.5	1333	1189.5	58150	23.5
	Caro	25	41	3941	62.7	795	11.8	1323	1180.9	58150	23.5
		25	46	3299	52.5	758	11.3	1302	1162.3	58150	23.5
		25	51	2283	36.3	455	6.8	750	669.3	58150	23.5
		25	70	4914	78.3	769	11.4	1626	1451.6	58150	23.5
	Sandusky	30	42	4000	63.7	761	11.3	1489	1329.0	58150	23.5
		30	43	9823	156.4	2752	41.0	4372	3902.0	58150	23.5
		30	64	3693	58.8	564	8.4	1125	1004.3	58150	23.5
	Saginaw	25	48	4609	73.4	776	11.6	1655	1477.4	58150	23.5
		25	69	5082	80.9	773	11.5	1455	1299.0	58150	23.5
		25	70	4685	74.6	776	11.6	1447	1291.7	58150	23.5
		25	73	4939	78.6	855	12.7	1554	1386.7	58150	23.5
	Mean			4376	69.7	844	12.6	1538	1372.4	58150	23.5

* Note: The values for sugarbeets are the same for all soils and for all stations due to the limitation of the YIELD model and availability of the weather data.

Table 9. Simulated Average Crop Yields at the Mean Level

	Location	Period (yrs.)	Soil #	Corn		Soybean		Drybean		Sugarbeet*	
				kg/ha	bu/ac	kg/ha	bu/ac	kg/ha	lbs/ac	kg/ha	tons/ac
Irrigated	Bad Axe	30	40	9531	151.7	2428	36.1	5012	4473.2	69210	28.0
		30	41	10279	164.0	2912	43.3	5100	4551.6	69210	28.0
		30	74	10488	167.0	2892	43.1	5098	4550.6	69210	28.0
	Caro	25	41	11261	179.3	3263	48.6	4787	4273.0	69210	28.0
		25	46	10510	167.3	2696	40.1	4705	4199.4	69210	28.0
		25	51	10684	170.1	3087	46.0	4746	4236.3	69210	28.0
		25	70	11612	184.9	2960	44.1	4721	4213.3	69210	28.0
	Sandusky	30	42	10720	170.7	2840	42.3	4795	4280.0	69210	28.0
		30	43	11407	181.6	3154	46.9	4815	4297.6	69210	28.0
		30	64	10756	171.2	2473	36.8	4729	4220.5	69210	28.0
	Saginaw	25	48	11656	185.5	3101	46.2	4527	4040.9	69210	28.0
		25	69	11554	183.9	3048	45.4	4477	3995.1	69210	28.0
		25	70	11424	181.9	2979	44.3	4456	3977.1	69210	28.0
		25	73	10845	172.7	3255	48.4	4539	4051.2	69210	28.0
	Mean			10909	173.7	2935	43.7	4751	4240.0	69210	28.0
Nonirrigated	Bad Axe	30	40	5267	83.8	766	11.4	1464	1306.3	61382	24.9
		30	41	6512	103.6	1149	17.1	2512	2241.7	61382	24.9
		30	74	6862	109.2	1078	16.0	2404	2145.9	61382	24.9
	Caro	25	41	6661	106.0	1200	17.9	2196	1959.7	61382	24.9
		25	46	5104	81.2	1067	15.9	2106	1879.6	61382	24.9
		25	51	4252	67.7	708	10.5	1406	1255.2	61382	24.9
		25	70	7467	118.9	1183	17.6	2271	2027.1	61382	24.9
	Sandusky	30	42	8148	129.7	1200	17.9	2404	2146.1	61382	24.9
		30	43	10976	174.7	2969	44.2	4637	4138.5	61382	24.9
		30	64	6440	102.5	1010	15.0	2133	1904.2	61382	24.9
	Saginaw	25	48	7705	122.6	1377	20.5	2334	2083.3	61382	24.9
		25	69	7499	119.4	1302	19.4	2141	1910.9	61382	24.9
		25	70	7174	114.2	1269	18.9	2091	1866.7	61382	24.9
		25	73	7250	115.4	1371	20.4	2252	2009.8	61382	24.9
	Mean			6951	110.6	1261	18.8	2311	2062.5	61382	24.9

* Note: The values for sugarbeets are the same for all soils and for all stations due to the limitation of the YIELD model and availability of the weather data.

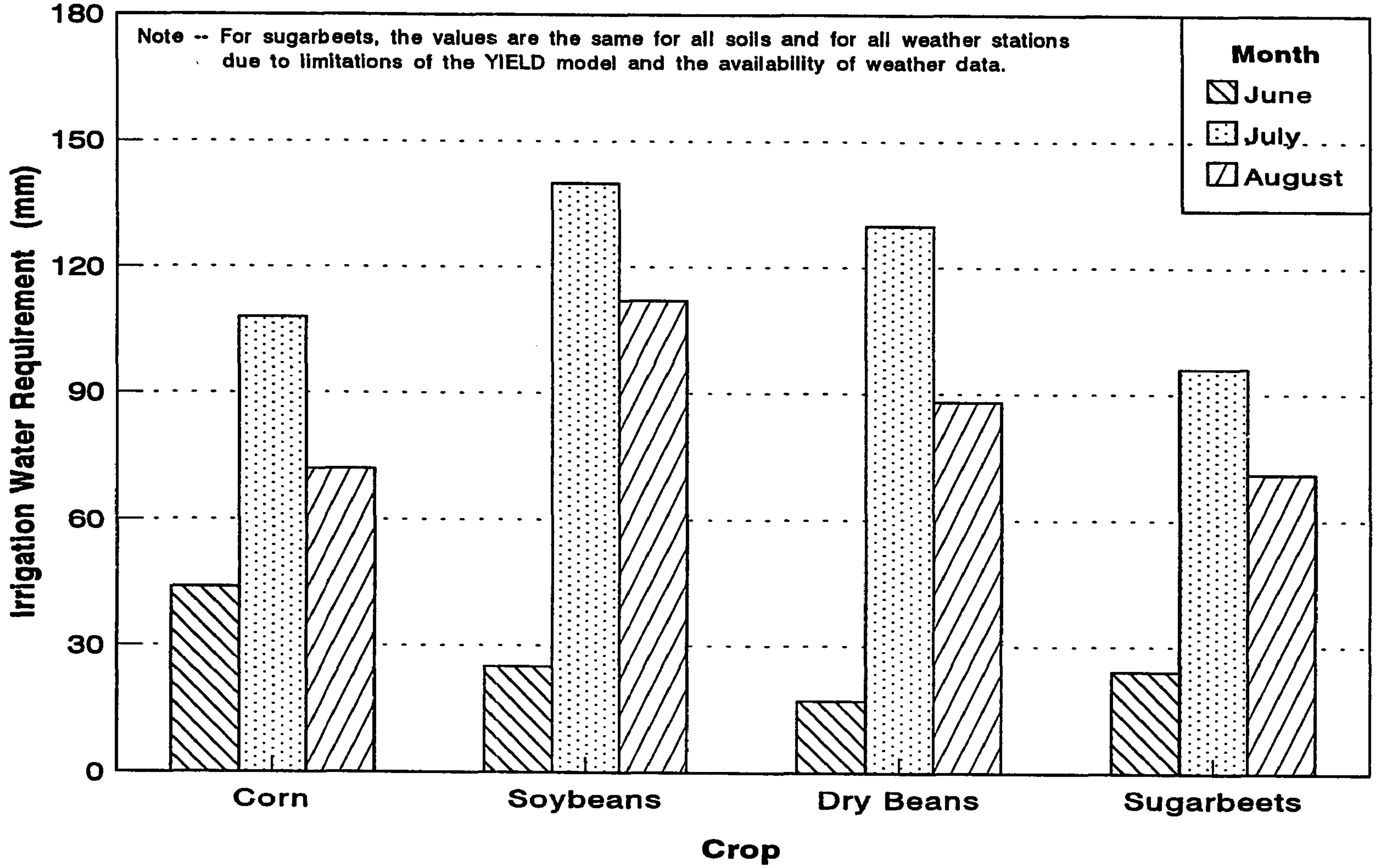

Figure 11. Simulated Irrigation Water Requirements at the 75th Percentile (June through August)

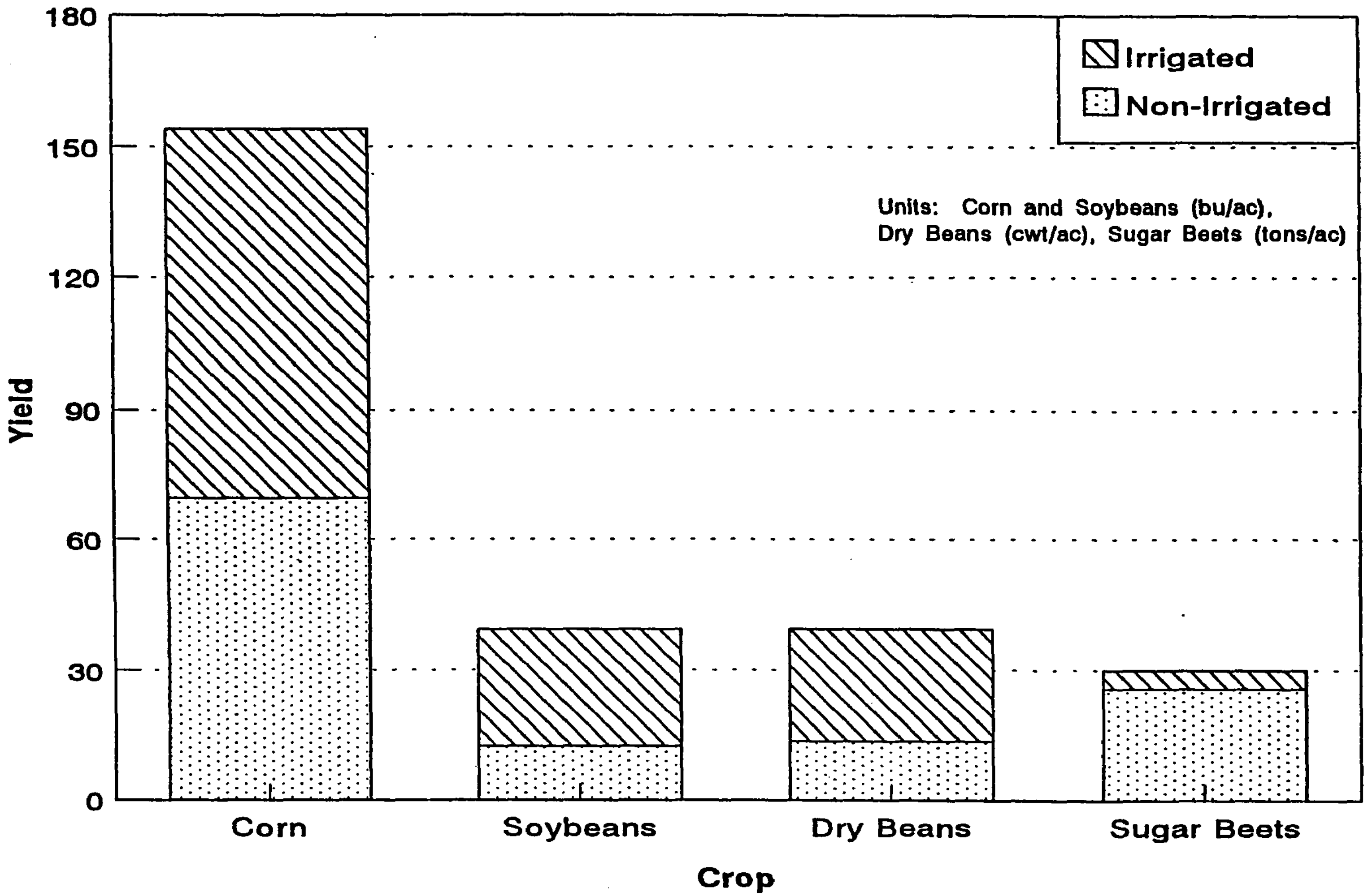

Figure 12. Comparison of Simulated Irrigated and Non-Irrigated Crop Yields in the Cass River Watershed

3.2 Total Irrigation Water Requirements in the Cass River Watershed

The average values of the irrigation requirements in July at the 75th percentile for each of the four crops (Table 6) were multiplied by the total acreage of agricultural land to derive the total irrigation requirements for the Cass River Watershed (Table 10). The results indicate that sugarbeets only require (at the 75th percentile) about 124,000 acre-feet of water for irrigation in July, which is the least amount among the four crops. That is, if all 392,713 acres of the total agricultural land in the Cass River Watershed were planted in sugarbeets, the minimum amount of water that would be needed in July to satisfy the irrigation need would be about 124,000 acre-feet. If any other single crop or combination of the four crops were planted in all the agricultural land in the watershed, a greater amount of water would be needed in July to meet the irrigation requirements.

4. TOTAL IRRIGATION WATER REQUIREMENTS IN THE SAGINAW BAY AREA

The total irrigation requirements at the 75th percentile for the entire Saginaw Bay five-county area were determined by multiplying the total acreage of agricultural land by the per acre irrigation water requirements. The results are shown in Table 11 and Figure 13. If all 2 million

Table 10. Total Irrigation Water Requirement for the 392,713 acres of Agricultural Land in the Cass River Watershed (If A Single Crop were Planted to the Total Acreage)

Item	Irrigation Demand in July at 75th Percentile			
	Corn	Soybeans	Dry Beans	Sugarbeets
Acreage Planted	392,713	392,713	392,713	392,713
Irrigation Demand in inches per acre	4.25	5.51	5.12	3.78
Total Irrigation Demand in acre-feet	139,090	180,320	167,560	123,700
Total Irrigation Demand in cfs	2,263	2,934	2,726	2,012

* One acre-foot is the amount of water needed to cover an acre of land to a depth of 1 foot.

Table 11. Total Irrigation Water Requirement for the 1,971,933 acres of Agricultural Land in the Saginaw Bay Area (If A Single Crop were Planted to the Total Acreage)

Item	Irrigation Demand in July at 75th Percentile			
	Corn	Soybeans	Dry Beans	Sugarbeets
Acreage Planted	1,971,933	1,971,933	1,971,933	1,971,933
Irrigation Demand in inches per acre	4.25	5.51	5.12	3.78
Total Irrigation Demand in acre-feet	698,390	905,450	841,360	621,160
Total Irrigation Demand in cfs	11,360	14,730	13,680	10,100

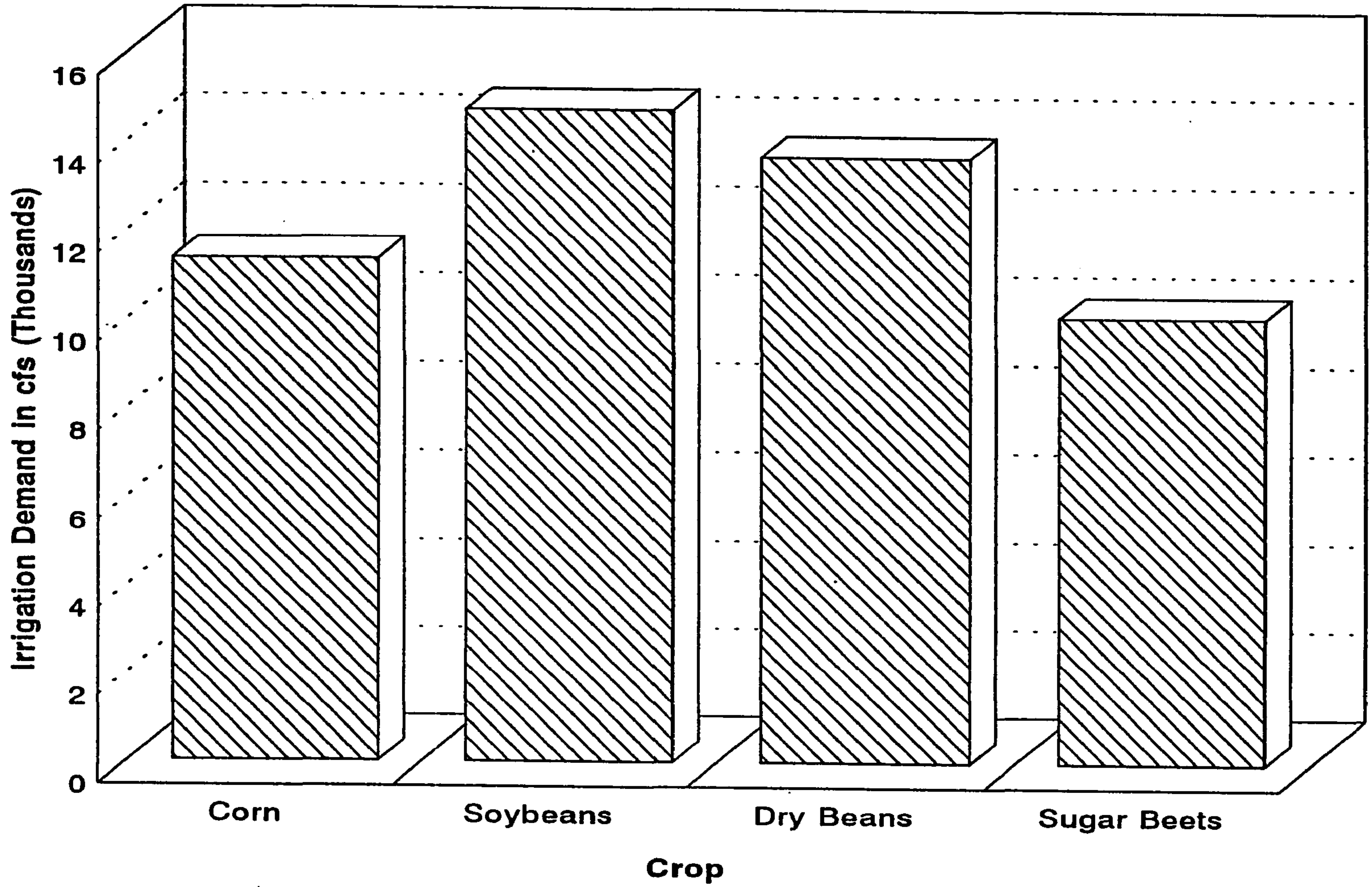

Figure 13. Total Irrigation Water Requirement in July at the 75th Percentile for Selected Crops Grown in the Saginaw Bay Area

acres of existing agricultural land were irrigated and planted in sugarbeets (the least water consumptive of the four crops), a total volume of about 621,000 acre-feet (or a flow rate of 10,000 cfs) of water would be needed in July in order to meet the irrigation requirement. If soybeans (the most water consumptive of the four crops) were planted and irrigated over the entire agricultural land area, a total volume of approximately 910,000 acre-feet of water would be required in July to meet the irrigation need. The total irrigation requirements for corn and dry beans in July over the entire agricultural land area are 7000,000 and 841,000 acre-feet, respectively. Greater July irrigation requirements for soybeans and dry beans, as compared to those for corn and sugarbeets, may indicate more frequent irrigation applications are needed for soybeans and dry beans in July. These simulated results need to be validated in the field in the Saginaw Bay area to avoid over- or under-statement.

5. LIMITATIONS OF THE SIMULATION MODELS

A simulation model is a mathematical representation of the physical system that has been chosen for study. Conceptually, it includes only those important, quantifiable factors and excludes factors that are difficult to quantify or less important. Since it only incorporates a portion of the factors that affect the physical system to be studied, even a validated simulation model has its limitations.

The four simulation models used in this study do not include the effects of diseases and pests on the development of the crops. The effects of nutrients deficiency (except nitrogen) on the growth of crops are not considered either. Thus, it is inevitable that differences exist between simulated and actually measured results. For the CERES-MAIZE model, after being evaluated in numerous locations, it has been reported that the model produced estimates of grain yields that had highly significant correlations with measured values (r^2= 0.52 -0.87). The measured data accounted for 52 to 87 percent of the variations found in the simulated data (Kiniry and Jones, 1986).

The comparison of the simulated non-irrigated crop yields in the Cass River Watershed with actual crop yields (1959-1980) in Tuscola County is shown in Table 12. The simulated yields of corn, soybeans and sugarbeets had highly significant correlations with the actual crop yields (α=0.01 for corn, α=0.05 for soybeans and sugarbeets). However, the actual crop yields only accounted for less than 40 percent of the variations in the simulated data. A large portion of the variations (up to 80 percent) found in the simulated yields was caused by errors. The simulated dry bean yields were poorly correlated with the actual yields from the period 1959-1980. Of the four simulation models, the CERES

MAIZE produced relatively accurate estimates of corn yield when compared to the actual corn yield.

Table 12. Correlation Analysis between the Simulated Non-Irrigated Crop Yields in the Cass River Watershed and the Actual Crop Yields (1959-1980) in Tuscola County

Crop	Regression Equation	r^2
Corn	Y = 26.66 + 1.10 x	0.36**
Dry Beans	Y = 14.93 + 0.54 x	0.03
Soybeans	Y = 6.24 + 0.60 x	0.20*
Sugarbeets	Y = 15.70 + 0.64 x	0.25*

Actual Yield Source: Michigan Department of Agriculture, 1959-1989.

The discrepancies between the simulated yields and actual yields may be partly attributed to the specifications of some of the input parameters. During the simulation, the soil conditions, planting dates, plant population, and fertilizer levels were fixed for all four crops over the period 1951-1980 because information on these parameters in each individual year was not available. Thus, the effects of chronology, soils, and management on crop yields may not be fully considered in some years. In addition, the simulated yields do not take into account the effects of pests and diseases on crop yields. Moreover, the simulated yields are at the watershed scale, whereas the actual crop yields were aggregated over the entire Tuscola County. This scale difference affects the comparability of the simulated yields and the actual county-wide data.

Table 13 shows the comparison of subsurface irrigated and non-irrigated crop yields in Huron County from the period 1987-1990 (LeCureux and Booms, 1987; 1988a, 1988b; LeCureux, 1989; 1990b). The results represent four years' study of corn, one year study of soybeans, two years' study of dry beans, and three years' study of sugarbeets. Subsurface irrigation increased corn yields by 6.6 percent in 1990 (a wet year) and by 78.9 percent in 1988 (a drought year). There was no difference between subsurface irrigated and non-irrigated soybean yields in 1989. For dry beans, subsurface irrigation did not result in increased yield in 1989 but increased the yield by 27.7 percent in 1990. Application of subsurface irrigation for sugarbeets increased yields by 6.9 percent in 1990 and by 38.9 percent in 1988. The amount of irrigation water applied for the four crops during the entire growing season ranged from 3.1 inches for dry beans, to 4.3 inches for soybeans and 6 inches for corn and sugarbeets.

It should be noted that the effects of subsurface irrigation on crop yields and irrigation water requirements may be different from those of other irrigation techniques such as flood irrigation or sprinkler irrigation. Thus, although application of subsurface irrigation did not result in an increase in soybean yield in 1989, application of other irrigation techniques may increase soybean yield.

Table 13. Comparison of Sub-Irrigated and Non-Subirrigated Crop Yields in Huron County

Year	Item	Corn	Soybean	Drybean	Sugar Beets
1987	NonIrrg.	115			
	Irrig.	164			
	Diff. (%)	42.6			
	Irrig. Amount (")	4.5			
1988	NonIrrg.	90			18
	Irrig.	161			25
	Diff. (%)	78.9			38.9
	Irrig. Amount (")	6.5			4.8
1989	NonIrrg.	160	39	21.6	22.5
	Irrig.	175	39	20.8	24.0
	Diff. (%)	9.4	0	-3.7	6.7
	Irrig. Amount (")	7.9	4.3	4.3	8.1
1990	NonIrrg.	147		18.8	26.2
	Irrig.	157		24.0	28.0
	Diff. (%)	6.6		27.7	6.9
	Irrig. Amount (")	5.5		1.8	5.0
Mean	NonIrrg.	128	39	20.2	22.2
	Irrig.	164	39	22.4	25.7
	Diff. (%)	28.1	0	10.9	15.6
	Irrig. Amount (")	6.1	4.3	3.1	6.0

Table 14 lists the mean simulated irrigated (1951-1980) crop yields and irrigation water requirements in the Cass River Watershed and the mean actual subsurface irrigated crop yields and irrigation requirements in Huron County (1987-1990). Information on the actual subsurface irrigated crop yields and amount of irrigation water applied is only available for up to 4 years (for corn) (LeCureux and Booms, 1987; 1988a, 1988b; LeCureux, 1989, 1990b). It is used here for reference since no long term records on subsurface irrigated crop yields is available.

Table 14. Comparison of the Mean Simulated Irrigated Crop Yields in the Cass River Watershed (1951-1980) with the Actual Subsurface Irrigated Crop Yields (1987-1990) in Huron County

Item		Corn	Soybean	Drybean	Sugar Beets
Yields	Actual	164.0	39.0	22.4	25.7
	Simulat.	173.7	43.7	42.4	28.0
	Diff.(%)	5.9	12.1	89.3	8.9
Irrig. Applied	Actual	6.1	4.3	3.1	6.0
	Simulat.	6.1	8.0	6.5	5.1
	Diff.(%)	0.7	84.9	111.0	-14.7

It can be seen from Table 14 that based on the limited information, the simulation models seemed to have produced relatively accurate estimates of the yields and irrigation water requirements of corn and sugarbeets but over-estimated the yield of dry beans by 89.3 percent. The irrigation water requirements of soybeans and dry beans were over-estimated by 85 and 111 percent, respectively. These differences may be related to the following factors: (1) long term subsurface irrigated crop records were not available; (2) effects of pests and diseases on crop yields and irrigation water requirements were not incorporated in the simulation models; (3) effects of subsurface irrigation techniques on crop yields and irrigation water requirements were not considered in the models; and (4) automatic irrigation was used in the simulation models during the simulation. That is, whenever there was a need for irrigation, the models adopted automatic irrigation so as to timely meet the irrigation water requirements of the crops. However, in the field operation, there may exist a time lag between the time when crops need water and the time that application of irrigation starts. This delay may result in physiological stress of the crops and eventually affect the crop yields.

In summary, like any other simulation models, the four simulation models used in this study have their limitations. The models yielded relatively accurate estimates of the yields and irrigation water requirements for corn and sugrbeets but overestimated yields and irrigation requirements for soybeans and dry beans by a large margin. Of the four simulation models used in this study, when compared to the actual yields and amount of irrigation water applied, the CERES MAIZE produced better accurate estimates of the corn yields and irrigation water requirements. To improve accuracy of the simulated yields and irrigation requirements in the study area, long term field experiments, beyond the scope of this study, must be conducted to verify the input parameters in the simulation models. This effort may well take up to several decades if a thorough field validation is desirable.

The four simulation models used in this study were to demonstrate how they can be used in developing a framework for irrigation development. If the simulated results are to be used for decision making, errors associated with the simulated results must be considered. In addition, validation of the models in the field is strongly recommended. Subsequent studies which are oriented to decision making must carefully verify the models and collect better data sets so as to reduce the difference between simulated and observed crop yields and irrigation requirements.

II. THE SUSTAINABILITY OF GROUNDWATER RESOURCES FOR IRRIGATION DEVELOPMENT

1. HYDROGEOLOGIC SETTING

Glacial deposits in the study area have a thickness of 10 to 130 feet and are primarily clay underlain in places by sand and gravel. In some places, the clay extends from the land surface to the bedrock surface; while in other places, sand and gravel beds ranging in thickness from a few feet to 60 feet occur in the lower part of the glacial deposits. Clay yields little or no water to wells, whereas sand and gravel beds yield sufficient water to some wells for domestic needs (Davis, 1909; Twenter and Cummings, 1985; Sweat, 1992).

Bedrock units in the study area include the Saginaw Formation, the Bayport Limestone, the Michigan Formation, the Marshall Formation, and the Coldwater Shale (Figure 14). The Saginaw Formation was deposited during the Pennsylvanian Period; the other four bedrock units were deposited during the Mississippian Period. The Saginaw Formation is the first unit encountered below the glacial drift in the western part of the study area. It has a thickness of 100-300 feet and consists primarily of shale and silty shale (Twenter and Cummings, 1985). Underlying the Saginaw Formation is the Bayport Limestone, which is principally a fossiliferous, cherty limestone, often intermixed with

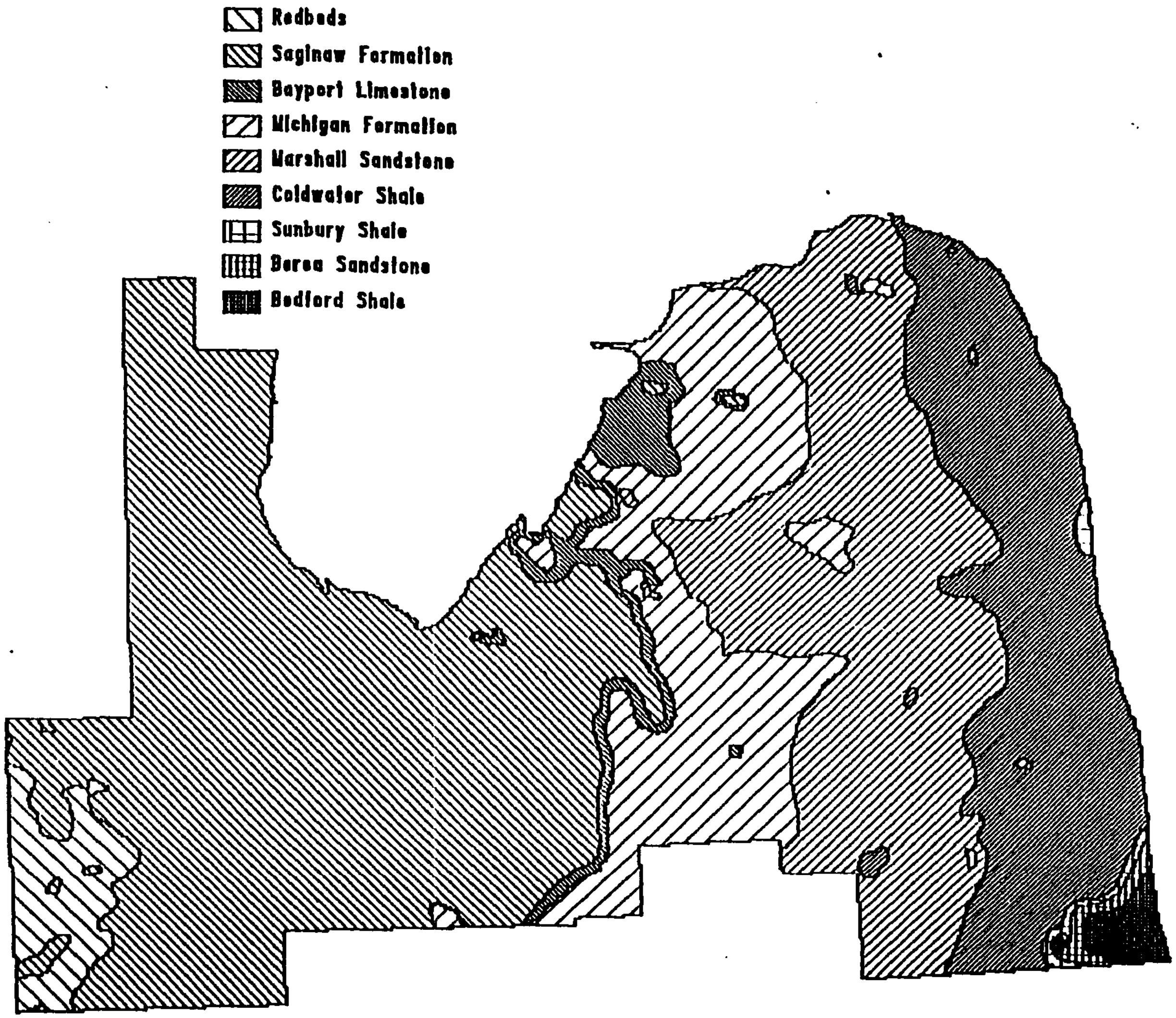

Figure 14. Bedrock Geology of the Saginaw Bay Area

sandstone (Sweat, 1992). Underlying the Bayport Limestone is the 130-foot thick Michigan Formation. This unit is mainly a sandstone (Long et al., 1988). Below the Michigan Formation lies the Marshall Formation, which consists of 70-120 feet of sandstone with some interbedded shale lenses. The Marshall Formation, locally and elsewhere in the State where not deeply buried, is a good producer of potable water (Layne Northern Company, 1984b). Underlying the Marshall Formation is the Coldwater Shale. Outcroppings of the Coldwater Shale occur along the east shoreline of Lake Huron (Gordon, 1990).

2. THE AVAILABILITY OF GROUNDWATER

The availability of groundwater in the glacial deposits of the Saginaw Bay five county area is shown in Figure 15 (Twenter, 1966a). Statistical analysis using PC ARC/INFO reveals that wells in the glacial deposits may yield less than 10 gallons of water per minute (GPM) in 55 percent of the area, 10 - 100 GPM in 39 percent of the area, and 100 - 500 GPM in 6 percent of the area. This result, in terms of having sufficient groundwater to support expanded irrigation, is not promising.

The general availability and quality of groundwater in the bedrock deposits is shown in Figure 16 (Twenter, 1966b). GIS statistical analysis indicates that wells in bedrock layers may yield water at a rate of less than 10 GPM in 17

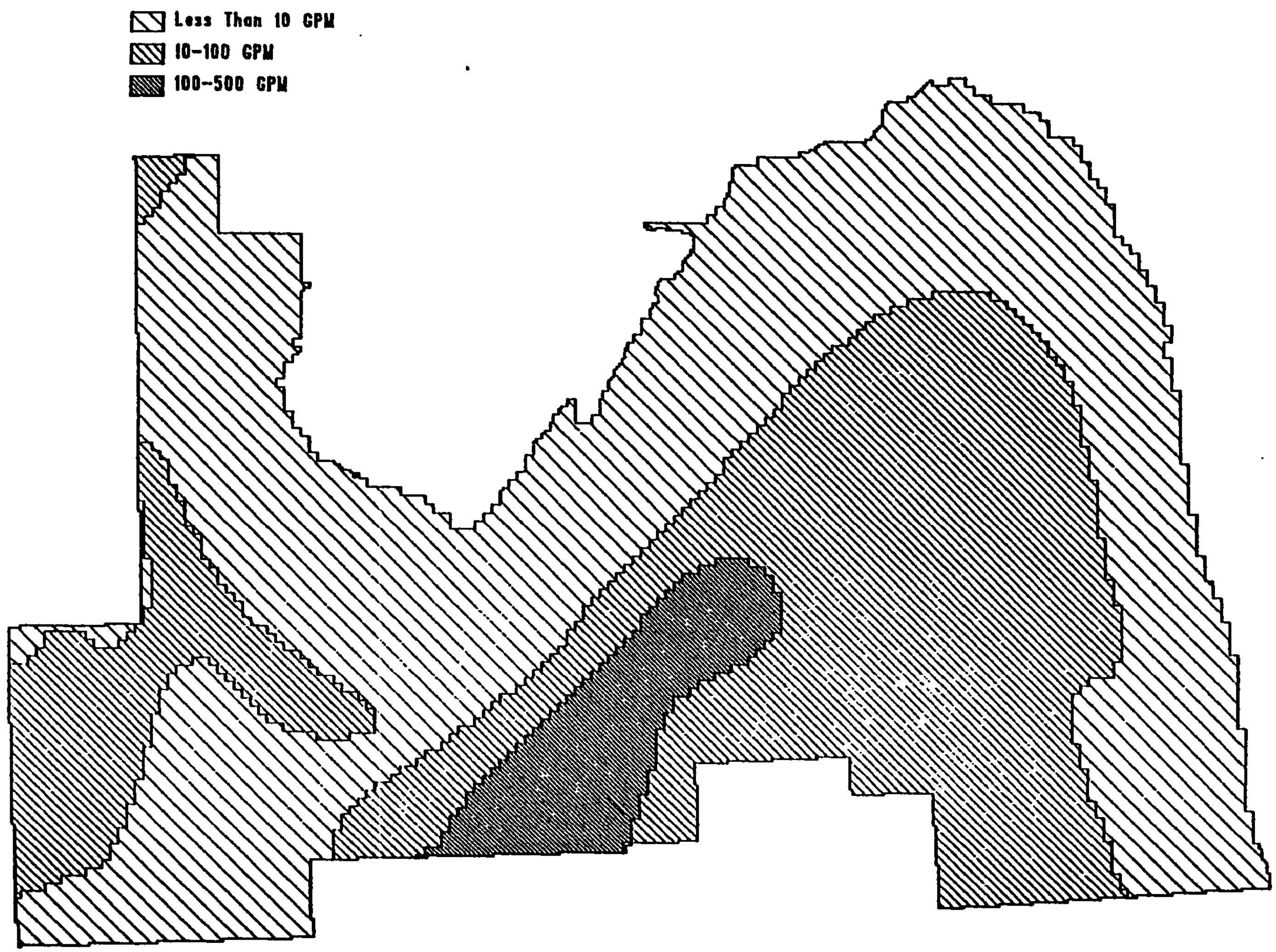

Figure 15. The Availability of Groundwater in the Glacial Deposits

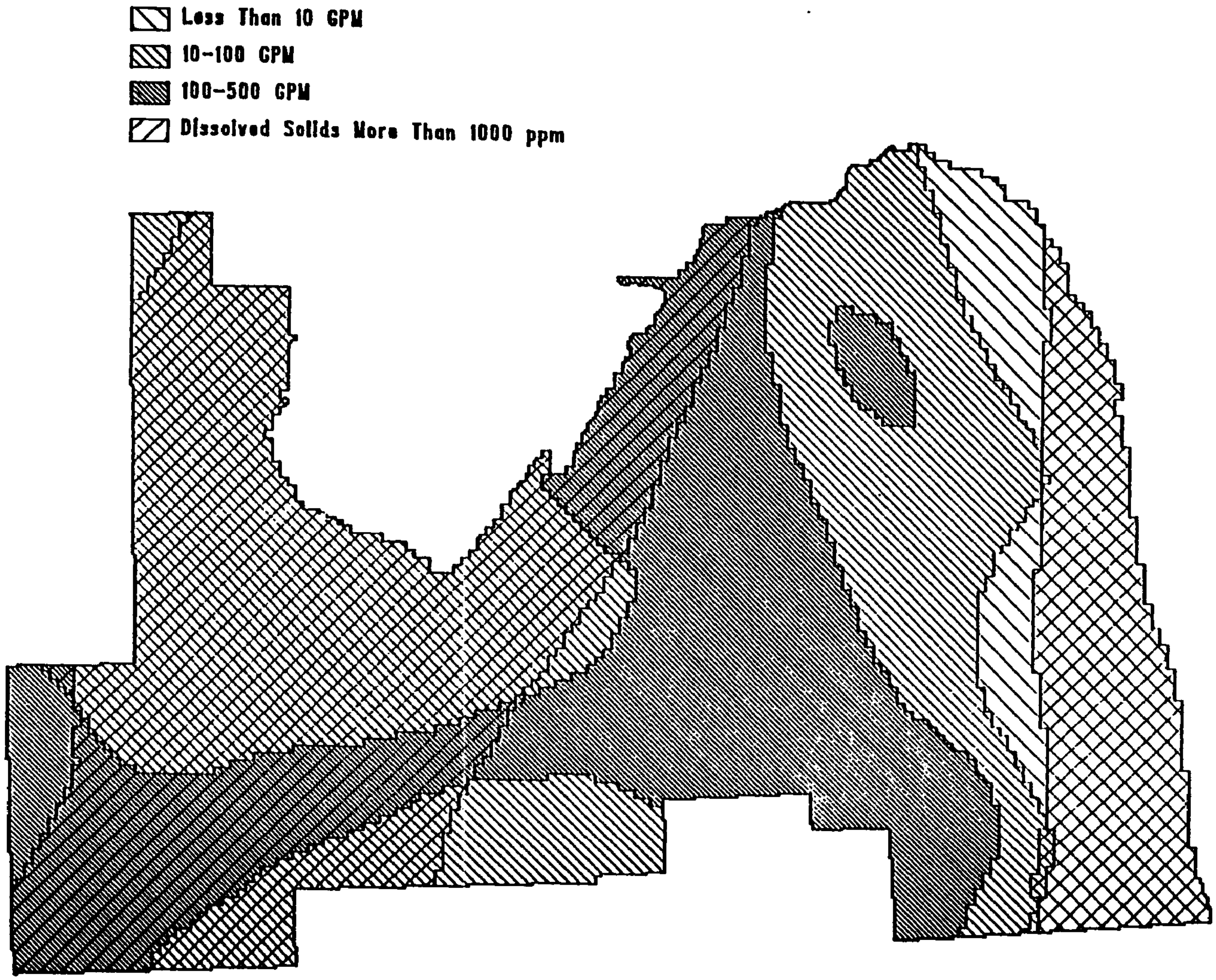

Figure 16. The Availability and Quality of Groundwater in the Bedrock Deposits

percent of the area, 10 - 100 GPM in 46 percent of the area, and 100 - 500 GPM in 37 percent of the area. However, in over 52 percent of the area, groundwater in the bedrock deposits is highly mineralized and has a dissolved solids content of more than 1,000 ppm (parts per million, equivalent to milligrams per liter, mg/L).

There exist great variations in the availability of groundwater in each individual bedrock unit. The Saginaw Formation is a poor source with respect to water supply. Although small quantities of water can be withdrawn from sandstone and siltstone beds, the water generally is highly mineralized in areas where the formation is in contact with sand and gravel glacial deposits. Under pumping conditions, more highly mineralized water would flow to the glacial deposits from the bedrock. Statewide, the mean dissolved solids concentration in water from the Saginaw Formation is about 1,629 mg/L (Twenter and Cummings, 1985).

Water from the Michigan Formation is generally saline and unsuitable for use. Because of high dissolved solids concentrations, water from the Michigan Formation is a potential source of elevated dissolved solids to the underlying Marshall Formation (Sweat, 1992).

The uppermost sandstone of the Marshall Formation is a good source of water for irrigation and domestic uses (Sweat, 1992). Yields of wells tapping this formation vary from 10 to 500 GPM (Twenter, 1966b). The dissolved solids concentration of water in this formation ranges from 181 to 2,440 mg/L (Sweat, 1992).

Wells tapping the Coldwater Shale yield small quantities of water with dissolved solids concentrations greater than 20,000 mg/L. Water in this formation is considered brackish and suitable only for livestock (Gordon, 1900; Sweat, 1992). Water from the Coldwater Shale may also be a source of dissolved solids to overlying sandstones in the lower part of the Marshall Formation, where pumping draws saline water upward from the shales (Sweat, 1992).

3. RECHARGE AND DISCHARGE

Recharge and discharge rates are essential information for evaluating the sustainability of groundwater for irrigation. Estimates of the recharge and discharge rates in the study area are described below:

3.1 Estimate of Groundwater Recharge Rate

A. Equations

Groundwater recharge is the process by which water infiltrates the unsaturated zone and is added to the zone of saturation. Major sources of recharge to drift aquifers include infiltration of precipitation, natural or induced infiltration from surface waters, and upward leakage from underlying till or bedrock (Morrissey, 1989). In this study, precipitation is assumed to be the only source of groundwater recharge for estimating the recharge rate. Figure 17 shows the process of groundwater recharge from precipitation in a watershed.

As shown by Figure 17, after dropping to the ground, a portion of the precipitation infiltrates into the soil, and a portion of it becomes surface runoff when the rainfall rate exceeds the soil infiltration rate. Infiltrated water supplements soil moisture lost from soil evaporation and plant transpiration (ET). When the soil moisture content reaches the field capacity (i.e. the maximum amount of water the soil can hold), deep percolation, or recharge (R_c), occurs. In other words, the excess soil water reaches the water table and becomes stored in the aquifer.

The deeply percolating precipitation enters the groundwater reservoir. At the same time, a portion of the aquifer water, known as baseflow, discharges into streams and lakes. If infiltration causes the water table to rise, groundwater discharge into nearby streams will also increase.

According to the laws of mass conservation, the following equation is valid:

$$P = R_o + ET + D + \Delta S_s + \Delta S_g \qquad (1)$$

where P is precipitation, R_o is surface runoff, ET is evapotranspiration, D is groundwater discharge (i.e. baseflow to a stream), ΔS_s is change in soil moisture

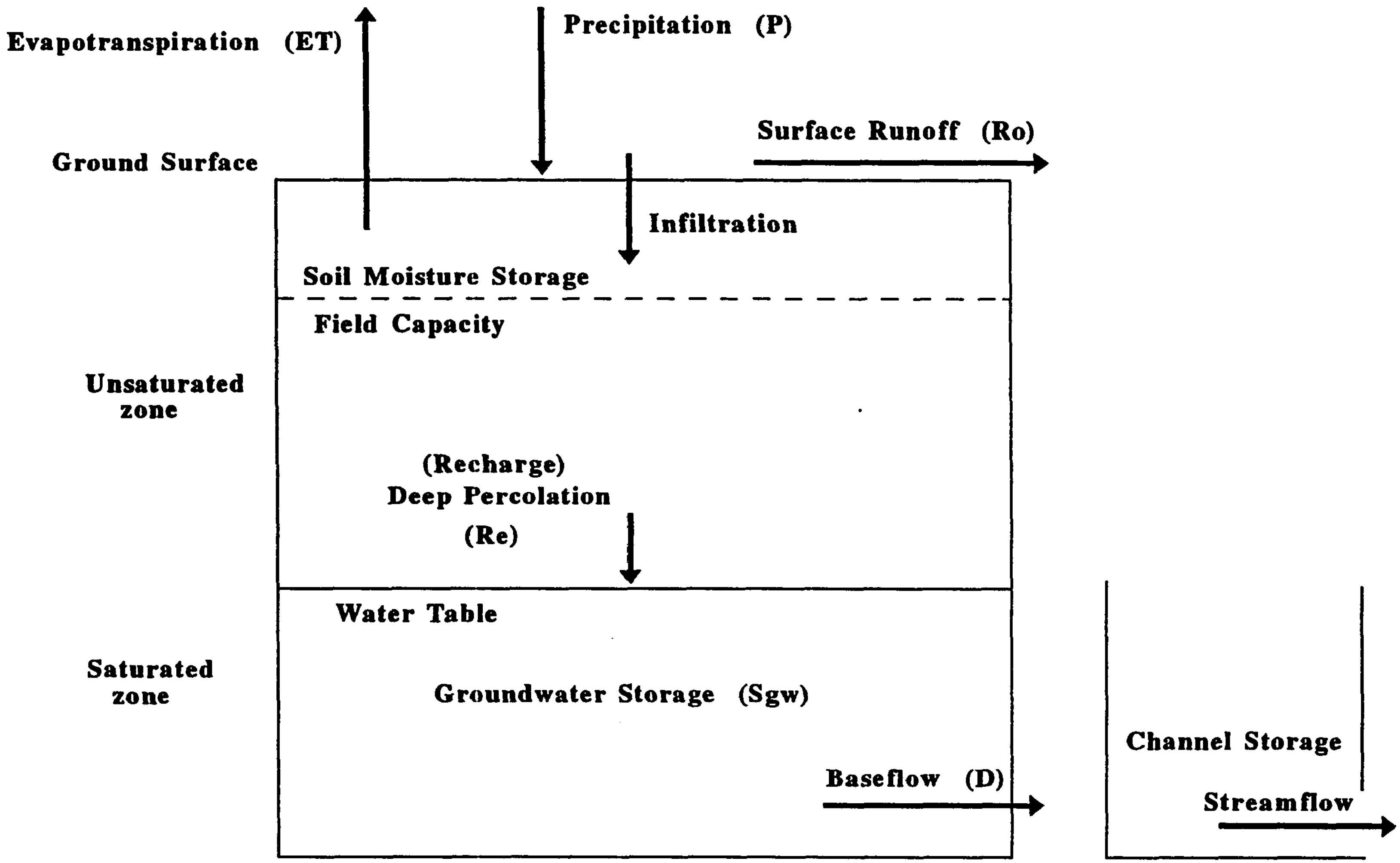

Figure 17. Conceptual Model of Groundwater Recharge

content in the unsaturated zone, and ΔS_g is change in groundwater storage.

Soil moisture is near field capacity during the winter and early spring of most years, and annual change in ΔS_s can be assumed to be negligible. By rearrangement, Equation (1) becomes:

$$P - R_o - ET = D + \Delta S_g \qquad (2)$$

Since $R_e = P - R_o - ET$ (3), then Equation (2) becomes

$$R_e - D = \Delta S_g \qquad (4)$$

Equation (3) can be used to estimate the groundwater recharge rate for a relatively long period of time by assuming that precipitation is the only input to the watershed[30].

Equation (4) shows that groundwater storage is dependent upon groundwater recharge and discharge. When groundwater recharge (Re) equals discharge (D), groundwater storage is at equilibrium and $\Delta S_g = 0$. If Re is smaller than D, groundwater storage will decline and reach a new equilibrium at a lower level. If too much water is withdrawn from the aquifer via pumping, groundwater discharge (D) will decrease and eventually reach zero.

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[30]Equation 3 is only used to estimate the groundwater recharge rate in watersheds where precipitation is the only input. In areas where regional flow, infiltration of surface water, and upward leakage from underlying layers exist, Equation 3 should incorporate these factors.

B. Estimates of Recharge and Discharge

Precipitation data sets for the years 1951-1980 were acquired from the Michigan Department of Agriculture Climatology Program for the Bad Axe, Caro, Flint, Midland, Saint Johns, and Sandusky weather stations. Mean annual precipitation over the period of 1951-1980 for each of the watersheds is shown in Table 15.

Streamflow data for as many as 78 years were obtained from the U.S. Geological Survey for the Cass River at the Frankenmuth gage station, the Black River near the Fargo gage station, the Flint River near the Fosters gage station, the Pigeon River near the Owendale gage station, the Shiawassee River at the Owosso gage station, and the Tittabawassee River at the Midland gage station (see Figure 31). Stream hydrographs were derived from the acquired streamflow data and were separated into the components of baseflow (D) and surface runoff (R_o). This was accomplished by using a hydrograph separation method described by Freeze and Cherry (1979).

The evapotranspiration rate (ET) was estimated by using CERES-MAIZE, a corn growth simulation model, and pan evaporation data from both the Michigan State University Saginaw Valley Beet and Bean Research Farm and the East Lansing Weather Station. It was assumed that the annual ET in the study area approximately equals the ET rate during the period of April through October. The amount of ET

Table 15 . Estimates of Recharge and Discharge in The Saginaw Bay Area of Michigan (Based on Weather Data from 1951-1980 and 30-78 years of Streamflow Data (inches/yr))

Watershed	P - ET - Ro = Re			Re - D = ΔSg			$(Q_{25}/Q_{75})^{1/2}$
	P	ET	Ro	Re	D	Δ Sg	
Black River	27.96	22.47	3.58	1.91	4.72	-2.81	2.76
Cass River	28.22	22.47	3.37	2.38	5.01	-2.63	2.48
Flint River	29.19	22.47	3.18	3.54	5.29	-1.75	2.07
Pigeon River	29.35	22.47	3.94	2.94	4.30	-1.36	2.48
Shiawassee River	30.09	22.47	3.03	4.59	5.25	-0.66	1.98
Tittabawassee	28.71	22.47	3.10	3.14	6.02	-2.88	1.86

Note: P=precipitation, ET=evapotranspiration, Ro=surface runoff, Re=recharge, D=baseflow, ΔSg=change in groundwater storage, Q_{25} and Q_{75} are exceedence flows at the 25 and 75 percent level, respectively, and $(Q_{25}/Q_{75})^{1/2}$ is a flow ratio. A low flow ratio is an indication of a permeable basin that has a large storage capacity.

during periods of freezing temperatures (November through March) is negligible. The mean ET estimate of 19.30 inches between May and September was derived by computing the average value of simulated ET rates of non-irrigated corn in all 12 soil associations in the Cass River Watershed over the period of 1951-1980 (see Table 16). The monthly ET rates for April (1.89 inches) and October (1.28 inches) were estimated by multiplying the Class A Pan evaporation values for April and October that were measured on the Saginaw Valley Beet and Bean Research Farm during the period of 1986 to 1989, by 0.5 (Doorenbos and Pruitt, 1977). It was found that the mean annual ET estimate for the Cass River Watershed is 22.47 inches.[31]

Table 15 shows groundwater recharge and discharge rates and changes in storage. The annual groundwater recharge rates due to precipitation range between 1.91 and 4.59 inches. The lowest recharge rate of 1.91 inches is in the Black River Watershed near Fargo, where the bedrock formation is Coldwater Shale which yields small quantities

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[31]ET may be the most difficult variable to estimate in the equation. Although there are always errors associated with ET estimates, the annual ET of 22.47 inches is believed to be a reliable estimate since (1) the mean ET value of simulated irrigated corn in all the 12 soil associations in the Cass River Watershed during the period of 1951-1980 is 21.87 inches, and (2) the crop reference ET (ETo), derived by multiplying the mean Class A Pan evaporation value of April through October during the period of 1949-1980 (from the East Lansing weather station) by 0.7, is 27.31 inches. Thus, annual ET rate in the study area should range between 22 and 27 inches. Error in the annual ET estimate of 22.47 inches may range between 2 and 20 percent.

Table 16. Seasonal Cumulative ET (May though September) Estimated by the CERES-MAIZE Model for Non-irrigated Corn in the Cass River Watershed (Based on Weather Data from 1951-1980)

Weather Station	Period (yrs.)	Soil Association	ET (inches)
Bad Axe	30	40	16.77
	30	41	19.21
	30	73	19.92
	30	74	19.45
Mean			18.86
Caro	25	41	18.82
	25	42	19.06
	25	43	21.77
	25	46	17.32
	25	51	15.79
	25	64	18.78
	25	70	19.09
Mean			18.66
Sandusky	30	42	22.24
	30	43	21.57
	30	64	18.70
Mean			20.83
Saginaw C.P.	25	48	19.06
	25	69	18.90
	25	70	18.62
	25	73	18.86
Mean			18.86

Note: The mean seasonal ET for the entire Cass River Watershed is 19.30 inches.

of water with highly dissolved solids concentrations to wells. The flow duration ratio[32] of $(Q_{25}/Q_{75})^{1/2}$ is 2.76 in the Black River Watershed, which is the highest of all 6 watersheds, and indicates a low storage capacity in the watershed (Pettyjohn and Henning, 1979). The highest recharge rate of 4.59 inches is in the Shiawassee River Watershed, and the flow duration ratio is 1.98, which suggests a greater storage capacity in the river basin.

Annual baseflow (groundwater discharge) in the study area ranges between 4 and 6 inches, with the minimum occurring in the Pigeon River Watershed and the maximum occurring in the Tittabawassee River Watershed. It accounts for between 52 percent and 66 percent of the total streamflow. Of the six watersheds, Pigeon River has the lowest groundwater discharge rate (4.30 inches per year, accounting for 52 percent of the total flow). It was dry on several days each year over the period of 1986-1989 (U.S. Geological Survey Water Resources Data: Michigan, 1986-1989).

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[32]The shape of the flow duration curve is an index of the natural storage within a basin. During dry weather, the flow of streams is almost entirely from groundwater sources. The lower ends of duration curves indicate in a general way the characteristics of the shallow groundwater bodies in the drainage basin. When plotted on logarithmic probability paper, the more nearly horizontal the curve, the greater is the effect of groundwater storage. Similarly, the lower the flow ratio, the larger the capacity of the basin to store groundwater (Pettyjohn and Henning, 1979).

Groundwater recharge and discharge rates were also estimated using daily streamflow data for 1961 and from 1985 to 1989 for all six watersheds using the computer program developed by Pettyjohn and Henning (1979). Two methods, Local Minima and Sliding Interval, were used to estimate annual groundwater recharge and discharge rates. The results indicate that, during the periods of 1961 and from 1985 to 1989, the mean annual recharge rates estimated by the Local Minima method ranged between 2.80 and 5.51 inches, with the minimum occurring in the Black River Watershed (2.80 inches) and the maximum occurring in the Shiawassee River Watershed (5.51 inches) (Appendix A). During the same period, the mean annual recharge rates estimated by the Sliding Interval method ranged between 3.61 and 6.64 inches, with the minimum recharge rate occurring in the Pigeon River and the maximum recharge rate in the Flint River Watershed. The mean groundwater discharge rates varied between 3.32 and 6.38 inches (using the Local Minima method). The mean percentage of the groundwater discharge rate to the total streamflow (by using the Local Minima method) ranged between 40 and 67 percent, with the lowest (40%) in the Black River Watershed and the highest (67%) in the Shiawassee River Watershed. The mean recharge and discharge rates estimated by using the Sliding Interval method showed similar results (Appendix A). These estimates are very similar to the estimates in Table 15.

Change rates in groundwater storage (ΔS_g) are all negative numbers, which may indicate that the amount of water being added to the zone of saturation from precipitation is smaller than the baseflow (i.e. the amount of water flowing out of the aquifer to the stream). It may also suggest the existence of flowing wells in some areas. A study by Allen (1974) points out that flowing wells exist in the Saginaw Formation and Marshall Formation in the Saginaw Bay area. In either case, negative storage change rates serve as a signal that the aquifer water supply may be declining. A study by Sweat (1992) also indicates that there is a net discharge of groundwater from the aquifers into the streams of Huron County.

It should be noted that errors exist in estimating annual ET rates, which could lead to errors in estimates of recharge and change in groundwater storage (see Equations 3 and 4). In addition, changes in recharge (R_c) and storage change (ΔS_g) due to infiltration from surface waters and upward leakage from underlying bedrock were not considered in this study.

3.2 Direction of Groundwater Flow

Well log records that cover the period from 1969-1986 were obtained for Huron, Sanilac and Tuscola Counties[33] from the Michigan Department of Natural Resources Geological Survey Division, and were digitized using C-MAP. Static water elevations (above mean sea level) of the 218 drift wells and 1,157 bedrock wells were entered into SURFER, a computer graphic package for generating topographic surfaces, to derive the potentiometric surfaces of water in the drift and bedrock aquifers (Figures 18 and 19). The hydraulic heads are similar in both the drift and bedrock aquifers of Huron, Sanilac and Tuscola Counties (Figures 20 and 21). They are higher in the south and central areas and decrease toward the west and east. Thus, groundwater flows east toward Lake Huron and west toward Saginaw Bay, from the central areas of Huron, Sanilac and Tuscola Counties. In Bay County, groundwater flow in both the drift and bedrock aquifers is toward Saginaw Bay (Long et al., 1988).

The relative head between the drift and bedrock aquifers can indicate the direction of leakage. If the head in the overlying aquifer is less than the head below it, leakage is from the deeper aquifer to the overlying aquifer. In this case, the leakage is from the bedrock to the drift aquifer.

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[33]No well log records were collected for Bay and Saginaw Counties where the Saginaw Formation underlies based on the suggestion of the Saginaw Bay Subirrigation Project Groundwater Advisory Committee that generally, these is not much water available in the Saginaw Formation.

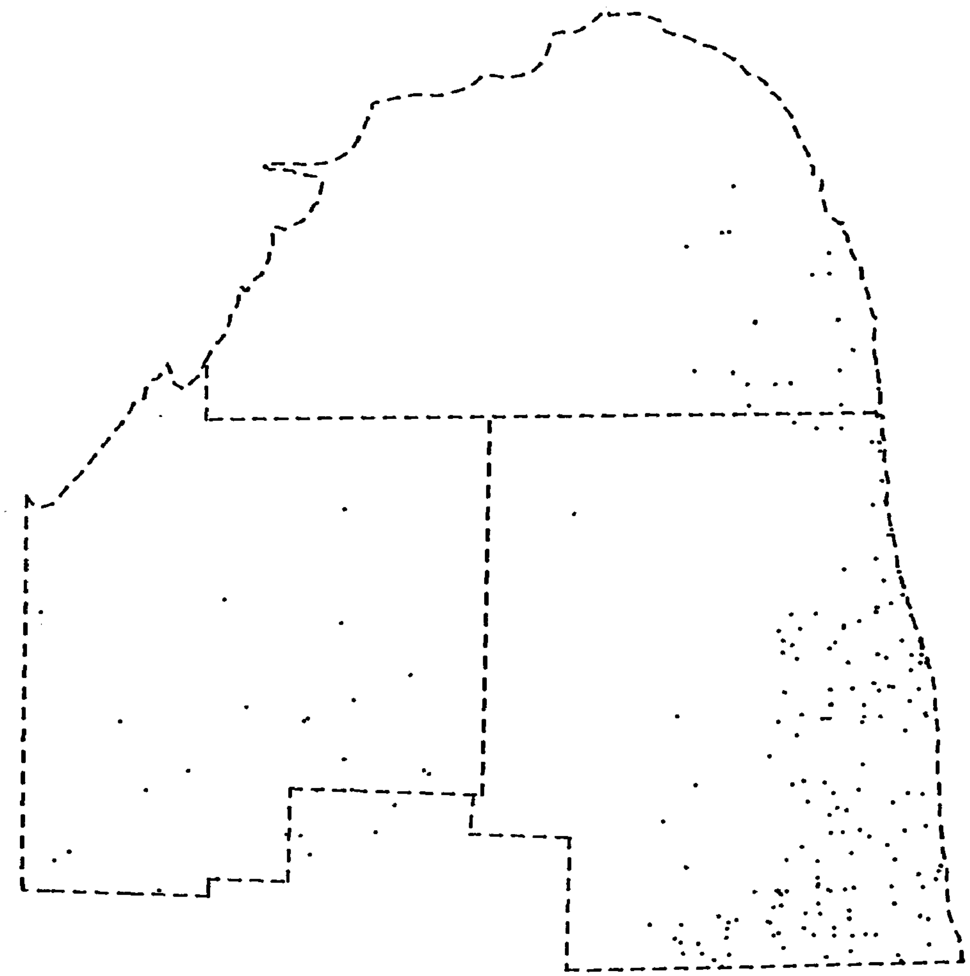

Figure 18. Locations of the Drift Wells

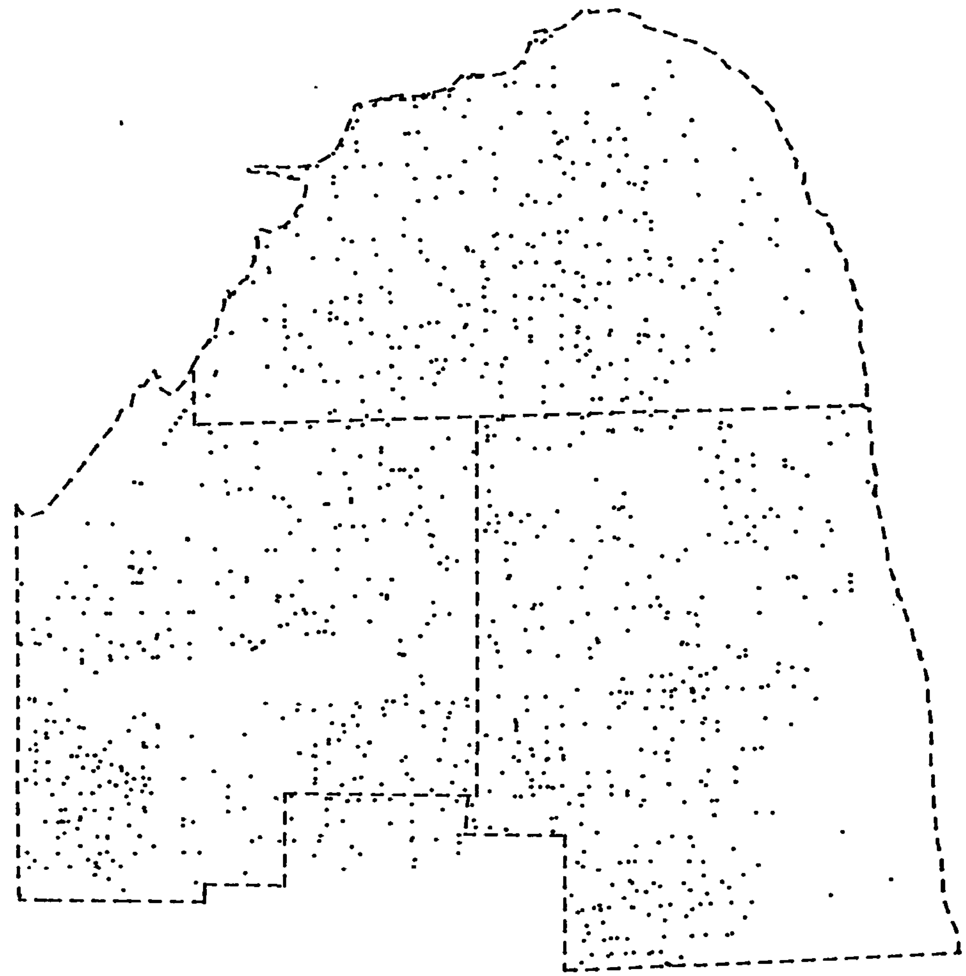

Figure 19. Location of the Bedrock Wells

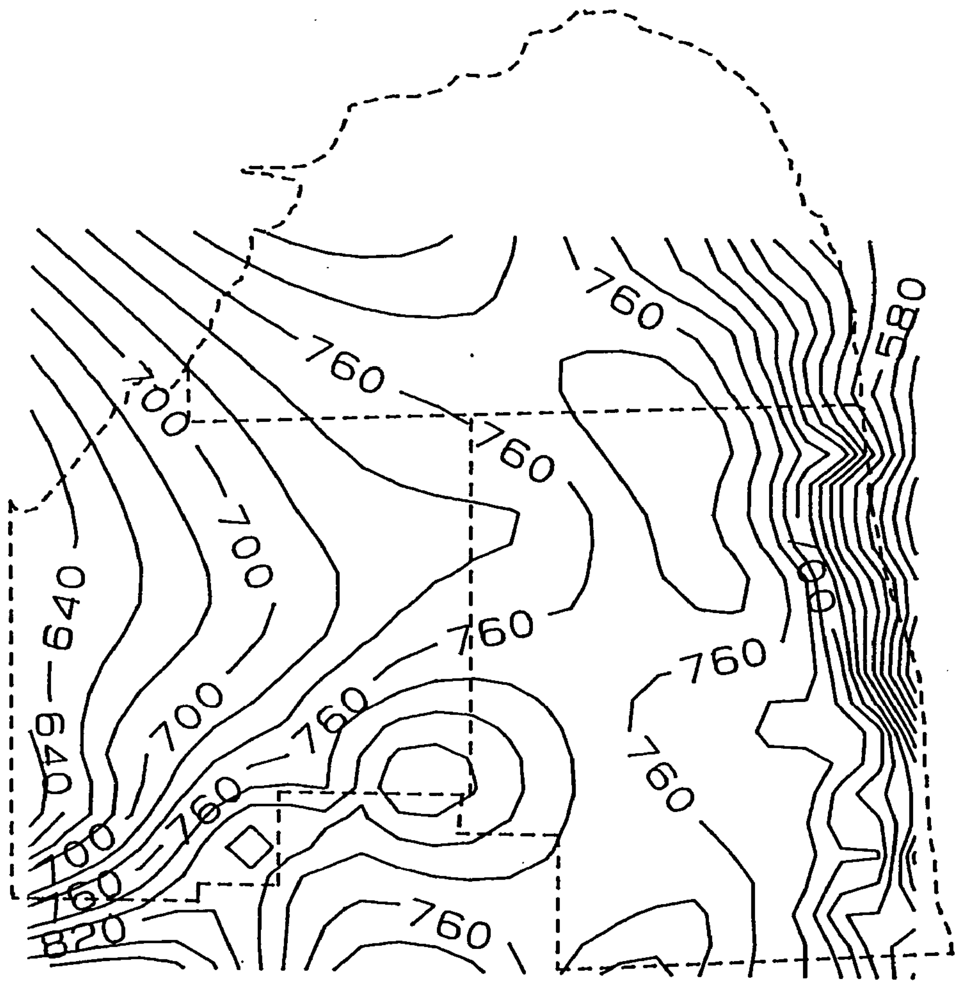

Figure 20. Potentiometric Surface (Feet above Sea Level) of Drift Aquifer

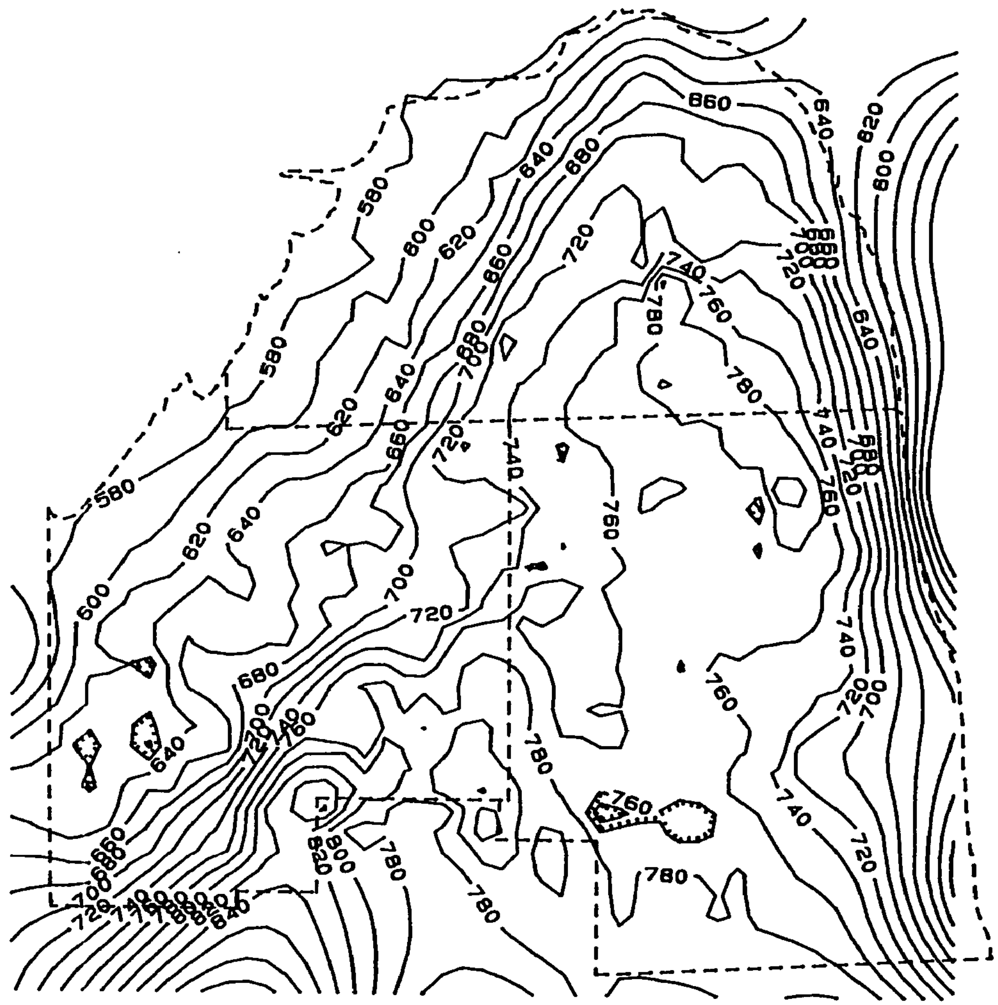

Figure 21. Potentiometric Surface of Bedrock Aquifers

This was determined by subtracting the bedrock potentiometric surface from the drift potentiometric surface (Long et al., 1988). The residual surface (Figure 22) shows that in the eastern and southwestern parts of the three county area, the bedrock aquifer has a higher head than does the drift aquifer, which indicates potential upward leakage from the bedrock to the drift aquifer (The presence of the flowing wells in this area has been reported by Allen (1974)). In the central and western parts of the three county area, the bedrock potentiometric surface is lower than the drift potentiometric surface. There is potential vertical flow from the drift aquifer to the bedrock aquifer. Hence, this area may be a groundwater recharging area, as high hydraulic head areas are recharge areas and low hydraulic head areas are discharge areas (Freeze and Cherry, 1979) (Figure 22).

4. SALINITY LEVEL IN GROUNDWATER

Partial chemical records covering the period from 1988 - 1989 were collected from the Health Departments of Huron, Sanilac and Tuscola Counties to evaluate the quality of groundwater. Unfortunately, of the 464 partial chemical records collected, only 129 of them could be located on the Land Atlas and Plat Books of the above three counties because no specific addresses were shown on the rest of the records. The 129 partial chemical records were digitized

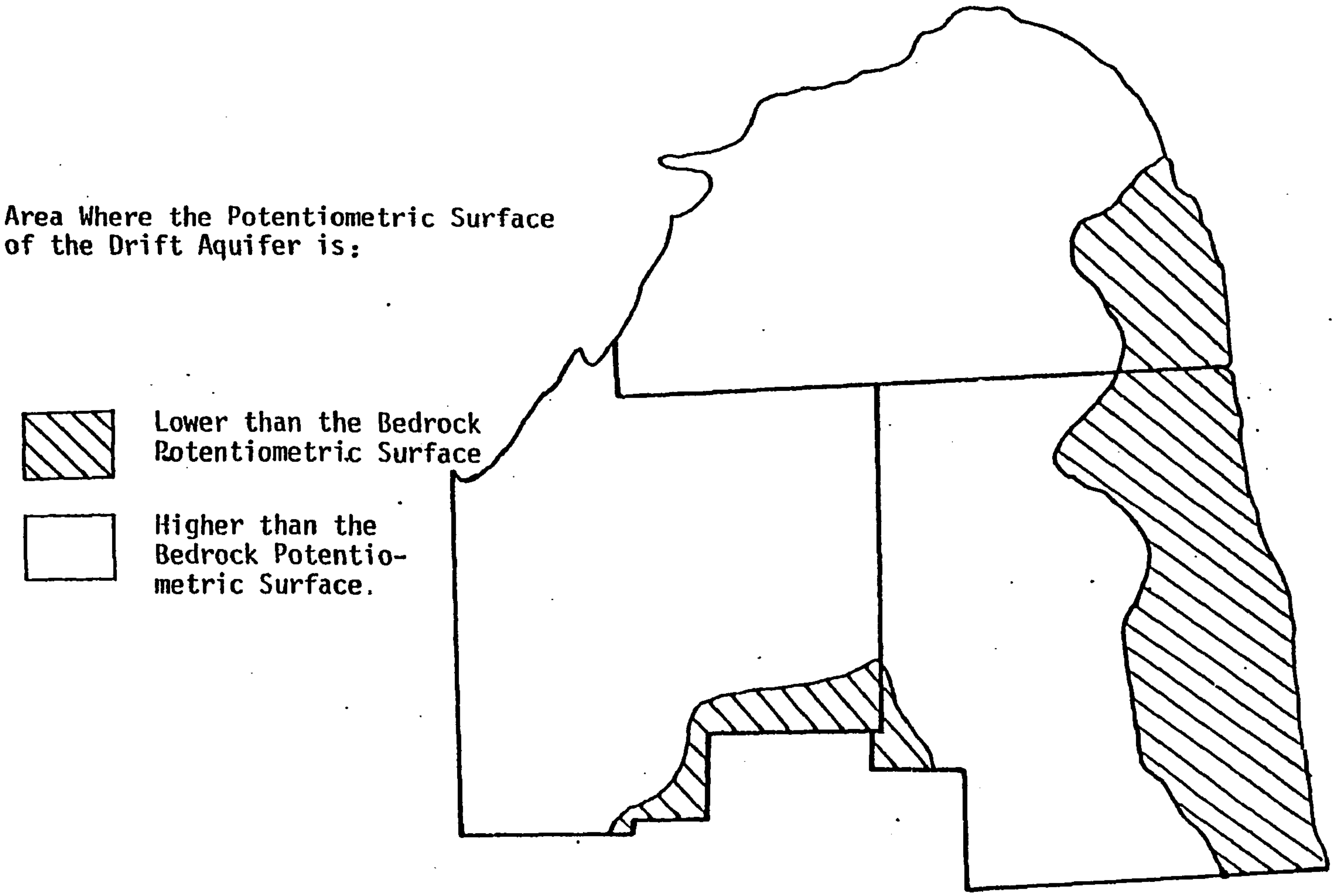

Figure 22. Residual Surface Obtained by Subtracting the Bedrock Aquifer Potentiometric Surface from the Drift Surface

using C-MAP and their locations are shown in Figure 23. Concentrations of chloride and sodium were chosen as indicators of brine levels in groundwater. Distributions (surfacing) of chloride and sodium concentrations were processed by SURFER. The results are shown in Figures 24 and 25.

As shown by Figures 24 and 25, concentrations of chloride and sodium in groundwater had a similar spatial distribution: they ranged between 100 and 400 mg/L along the eastern coast line where outcroppings of the Coldwater Shale occur. In addition, concentrations of the dissolved solids in this area exceed 1,000 mg/L. Concentrations of chloride and sodium varied between 100 and 400 mg/L in the northwestern corner, and were less than 100 mg/L in the central and western parts of the three-county area. The lower concentrations of chloride and sodium in groundwater in the central and western parts of the three-county area seemed to confirm that those areas where the bedrock potentiometric surface is lower than the drift potentiometric surface may be the recharge area.

If crops such as soybeans and dry beans, which have a low tolerance to salinity, are irrigated by groundwater with a chloride level greater than 142 mg/L or a sodium level greater than 69 mg/L, yield reduction and quality problems may occur. Severe problems may occur if the chloride level in irrigation water exceeds 355 mg/L (Bouwer, 1978). Thus,

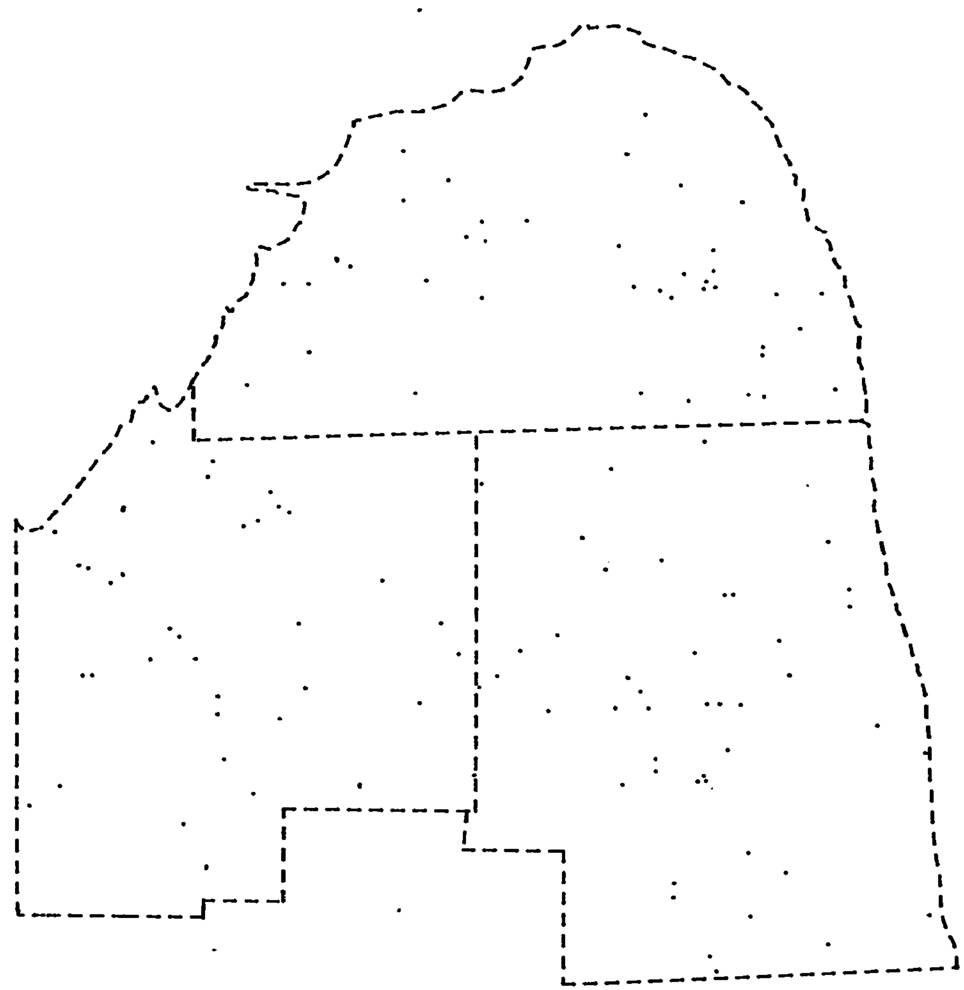

Figure 23. Location of Wells Sampled for Partial Chemistry Analysis

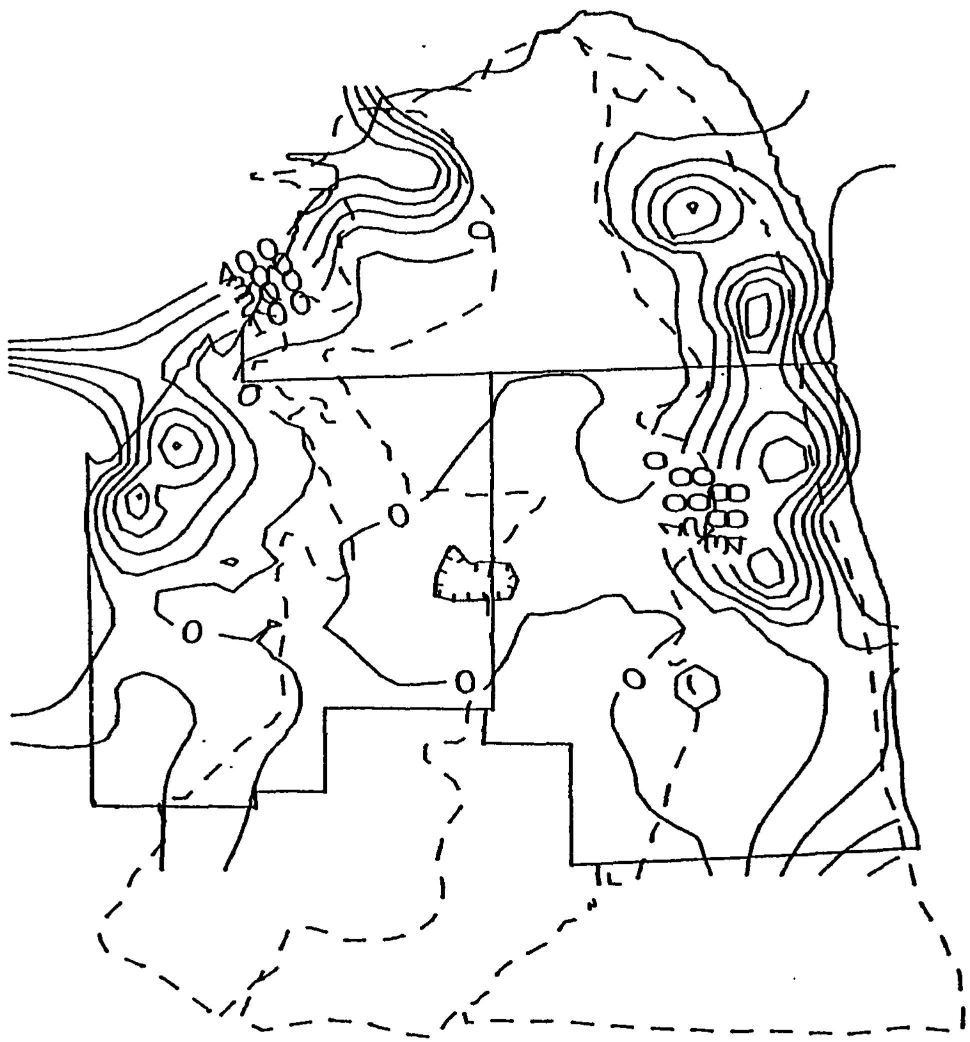

Figure 24. Concentrations of Chloride in Groundwater (Dashed Lines Represent the Michigan, Marshall, and Coldwater Formations, from Left to Right)

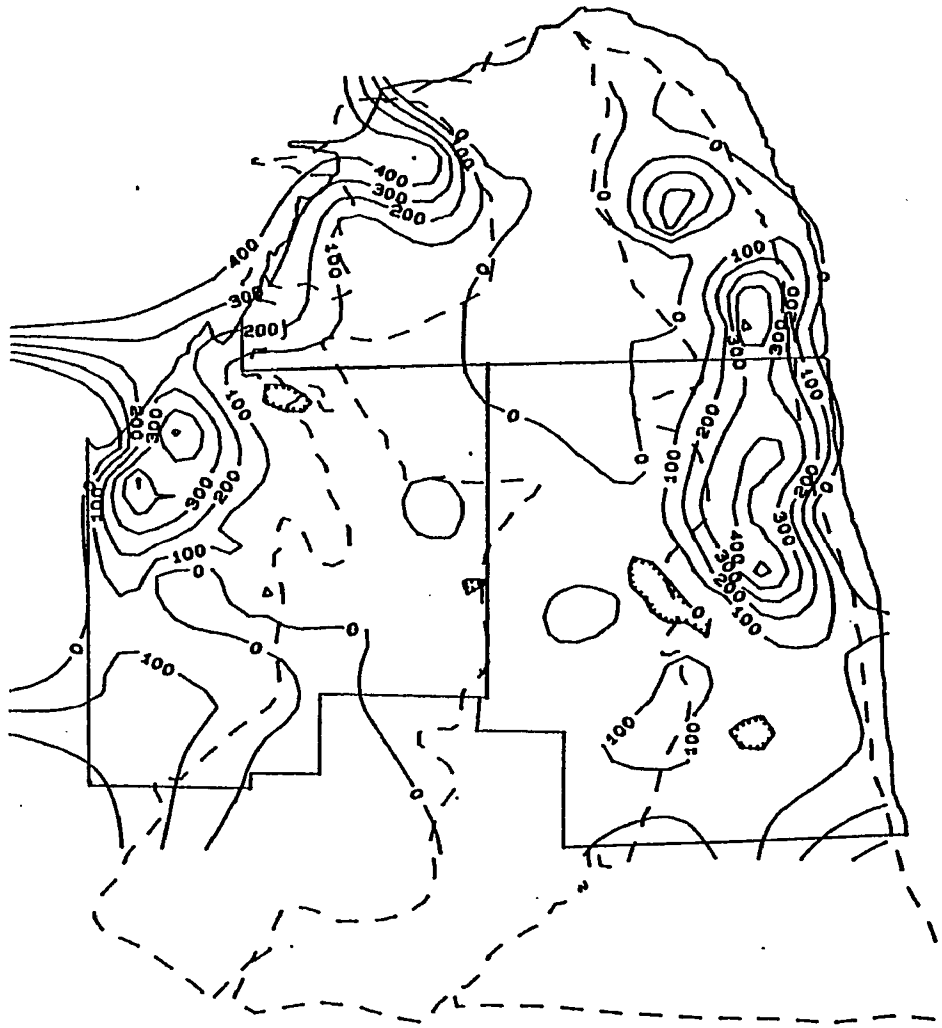

Figure 25. Concentrations of Sodium in Groundwater

groundwater along the eastern coastline and in the northwestern corner of the three county area should not be withdrawn for irrigation.

5. SUSTAINED GROUNDWATER YIELD

The magnitude of groundwater development depends on both the manner in which the effects of withdrawal are transmitted through the aquifer system and the changes in rates of groundwater recharge and discharge induced by the withdrawals. Over a sufficiently long period of time (prior to the start of withdrawals), an aquifer is in a state of equilibrium, and recharge (R_c) is balanced by discharge (D) from the aquifer, $R_c - D = 0$. Discharge from wells (i.e. pumping, represented by Q) superimposes a new discharge onto a previously stable system. The new discharge must be balanced by an increase in the recharge (R_c) of the aquifer, or by a decrease in the natural discharge (D), or by loss of storage in the aquifer (ΔS_g), or by a combination of these. This relationship can be expressed as:

$Q = R_c - D \pm \Delta S_g$ (Bredehoeft, et al. 1982) (5)

This equation indicates that water pumped from wells will be derived from (1) storage in the aquifer, (2) reduction of groundwater flow to nearby streams or lakes, and (3) possibly induced infiltration from streams or deeper aquifers (Morrissey, 1989). If the cone of depression ceases to expand, the rate of withdrawal is balanced by an increase in the rate of recharge or by a reduction in groundwater discharge to nearby streams or lakes. Under this condition:

$$Q = \Delta D + \Delta R \qquad (6)$$

Changes in recharge and discharge rates as a result of pumping can be referred to as capture, and the sustained yield of groundwater is limited by capture. Estimates of capture are important to groundwater planning for long term water supplies.

In the Saginaw Bay area, the Marshall Formation is the only good source of water for irrigation and domestic use. If pumping for irrigation continues on a relatively large scale, highly mineralized water would be induced either to move upward from the underlying Coldwater Shale or to move downward from the overlying Saginaw and Michigan Formations into the Marshall Formation. This would probably occur even before the reduction in the discharge rate can take place. In addition, more highly mineralized water would also flow from the Saginaw Formation to the glacial deposits in areas where the formation is in contact with sand and gravel deposits (Twenter and Cummings, 1985; Long et al., 1988; Sweat, 1992.). This indicates that ΔR (the induced recharge), although not zero, can not be used for irrigation.

If the groundwater discharge rate does decrease, the maximum amount of reduction (the worst consequence) would result in total depletion of the discharge, which would dry up many streams in the summer and lead to the destruction of valuable fisheries habitat. Thus, ΔD could be as much as the natural discharge rate, D, with the consequence of degradation of water quality and destruction of aquatic habitats.

6. POTENTIAL IRRIGATION EXPANSION AREA

The expansion of irrigation requires an adequate water supply. The above analysis indicates that water in the Saginaw Formation, Michigan Formation, and the Coldwater Shale is too highly mineralized, as these formations have dissolved solids concentrations greater than 1,000 mg/L, which exceed the U.S. Environmental Protection Agency's (EPA) drinking water maximum of 500 mg/L (Sweat, 1992). In addition, the salinity level (indicated by chloride and sodium concentrations) is high in these formations. If water with a high salinity level is used to irrigate crops that have a low tolerance for salinity, yield reduction and quality problems may occur (Bouwer, 1978). Thus, the Saginaw and Michigan Formations and the Coldwater Shale are not potential sources of irrigation water. The Marshall Formation is the only good source of water available for irrigation and domestic use (Sweat, 1992). However, continuous pumping of water for irrigation from this formation would induce highly mineralized water either to move upward from the underlying Coldwater Shale or to move downward from the overlying Saginaw and Michigan Formations to the Marshall Formation. Therefore, the withdrawal of groundwater for irrigation should be practiced cautiously in the Saginaw Bay area.

To be on the conservative side, this study assumes that the potential expansion of subsurface irrigation by groundwater lies in the areas where the soils are suitable (high and medium), the wells yield suitable water at the rate of 100 - 500 GPM and the concentration of dissolved solids is less than 1,000 mg/L. Based on this assumption, the general availability and quality of groundwater in the bedrock (Twenter, 1966b, Figure 16) is first superimposed on the bedrock geology map (Figure 14) to derive the general availability and quality of groundwater in the Marshall Formation. The resulting map is then superimposed on the map of soil suitability for subsurface irrigation (Figure 7) in order to estimate the maximum irrigation acreage that might be supported by groundwater in the Marshall Formation. The results are shown in Table 17 and Figure 26.

As shown by Table 17, groundwater with a yield of 100 - 500 GPM may be able to supply 160,000 acres of subsurface irrigable land, which represents 8.1 percent of the 2 million acres of the total agricultural land in the Saginaw Bay five-county area. The expansion, however, should proceed cautiously since the recharge of groundwater from precipitation is low in the study area, and since brine in the deep aquifer may move upward due to the large withdrawal of groundwater.

Table 17. Acreage of Potential Subsurface Irrigation Expansion Area with Suitable Groundwater Supply

Soil Suitability	Groundwater Yield (100-500 GPM)	Total (%)
High	15,541	8.6
Medium	144,177	80.2
Low (Not Suitable)	20,181	11.2
Total	179,899	100.0

7. SUMMARY

The above results indicate that:

1) Recharge due to precipitation, less surface runoff and evapotranspiration, ranges between 2 and 4.6 inches annually in the Saginaw Bay area.

2) Baseflow, resulting from discharges from groundwater storage, varies between 4.3 and 6.02 inches per year. Annual groundwater discharge accounts for between 52 and 66 percent of the total streamflow.

3) The difference between recharge and baseflow is assumed to be the change in groundwater storage. Negative values indicate the depletion of the regional groundwater storage. They may also indicate upward movement of groundwater from bedrock aquifers, such as occurs with

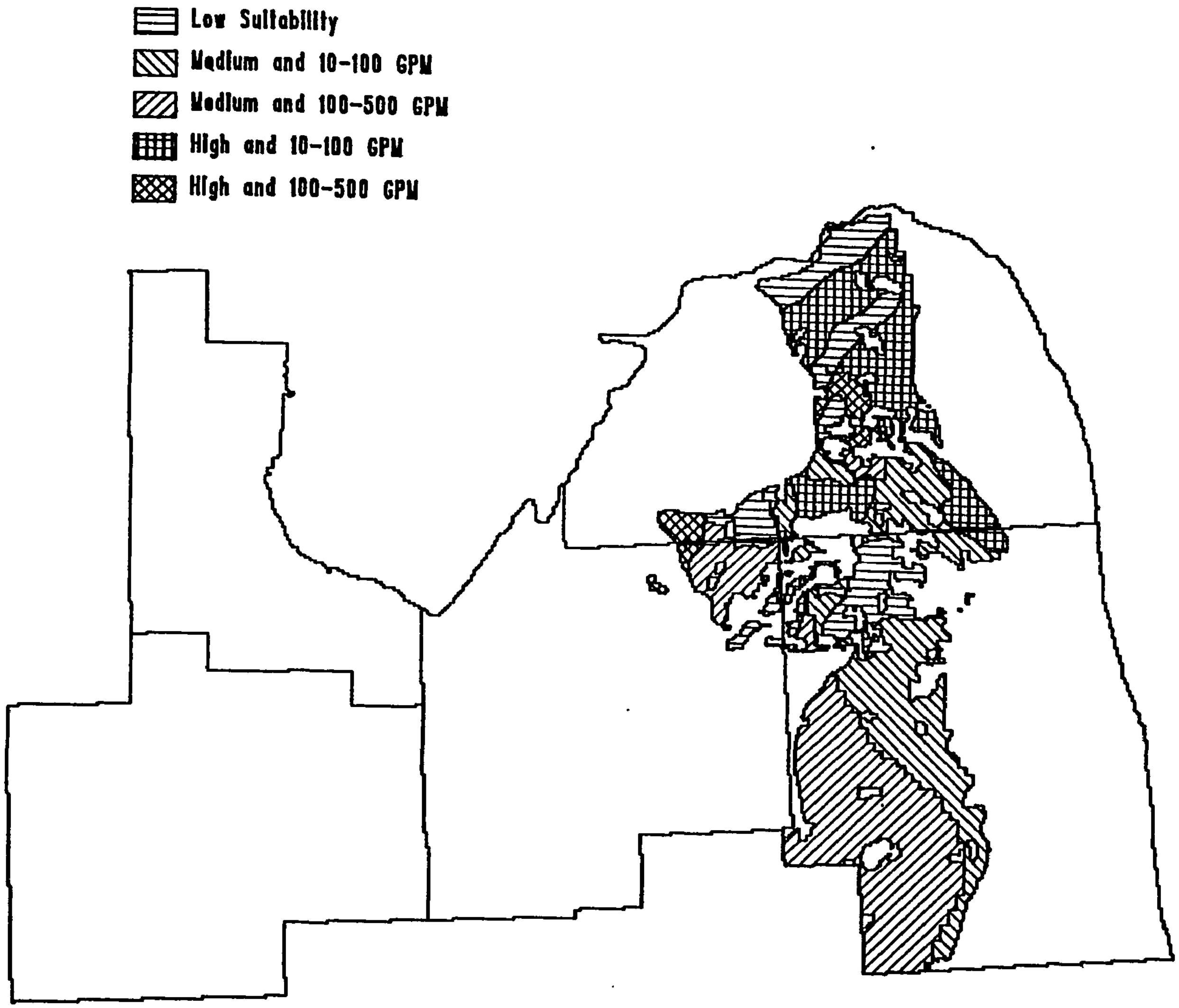

Figure 26. Potential Subsurface Irrigation Expansion Areas

artesian wells reported by Allen (1974). Uncertainty associated with the annual ET estimate may affect the estimates of recharge and change in groundwater storage.

4) Central Huron County, western Sanilac County, and eastern Tuscola County may be recharging areas based on well yields, water quality and hydraulic heads of aquifers.

5) Total dissolved solids concentrations and salinity levels (indicated by chloride and sodium concentrations) are lower in the potential recharging areas in these counties.

6) Potential subsurface irrigation development supplied by groundwater may lie in parts of central Huron County, southwestern Sanilac County and northeastern Tuscola County. The maximum irrigation acreage by groundwater supply could be 160,000 acres. However, use of groundwater for irrigation should be practiced cautiously since continuous pumping of groundwater would reduce the baseflow and induce the upward movement of brine from the deeper aquifer.

III. CAPACITY OF STREAMFLOW FOR IRRIGATION DEVELOPMENT

1. INTRODUCTION

As discussed above, the amount of groundwater available for irrigation in the Saginaw Bay area is limited; only 160,000 acres (8 percent of 2 million acres of the total agricultural land) may be subsurface irrigated with groundwater. Surface water may be used to increase the water available for irrigation expansion in the study area. However, since the withdrawal of water for irrigation from the Great Lakes is legally restricted, the availability of streamflow must be examined as a source of water for irrigation expansion. The Cass River Watershed (Figure 8) was chosen as a pilot study area to evaluate streamflow capacity for irrigation.

2. STREAMFLOW DURING THE IRRIGATION SEASON

In Michigan, the requirement for irrigation water is greatest in July and August when streamflow is at its lowest (Figure 27). Thus, the low flow period of July and August was chosen as the critical period. The flow rates of the Cass River were acquired from the U.S. Geological Survey for three gage stations: the Cass City Station on the upper stream, the Wahjamega Station on the middle stream, and the Frankenmuth Station at the mouth of the stream (Figure 8). The locations of the Cass City, Wahjamega and Frankenmuth

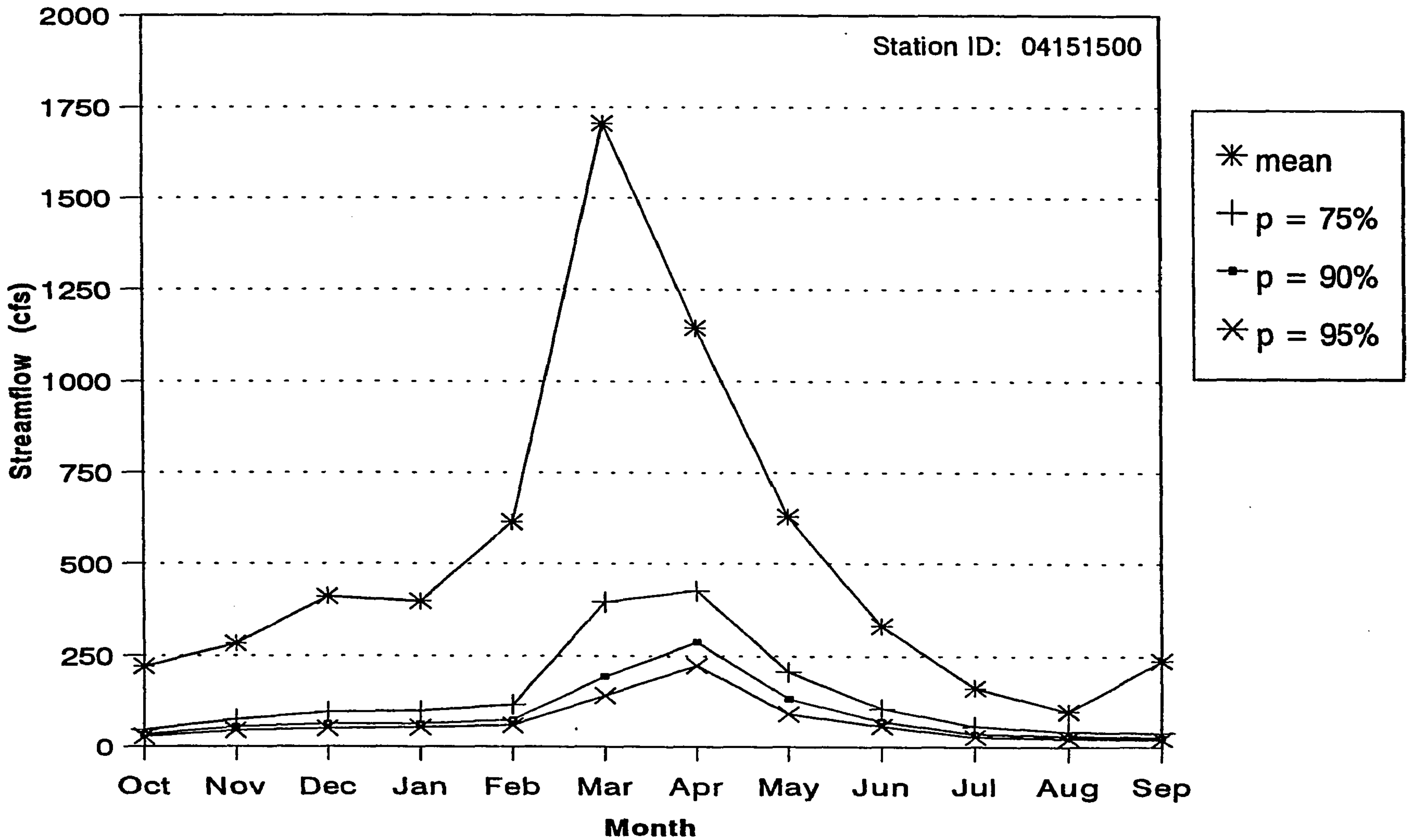

Figure 27. Exceedence Streamflow in the Cass River at the Frankenmuth Station (1936-1985)

gage stations were digitized using C-MAP and PC ARC/INFO. The exceedence flow rates of the Cass River at the three gage stations are shown in Figures 28, 29, and 30, respectively.[34]

Spatial analysis using ERDAS, a Geographic Information System, shows that 50.8 percent of the potentially irrigable agricultural land is within one kilometer (0.62 mile) of the Cass River. This indicates that it is likely to be technically feasible to withdraw water from the Cass River for irrigation expansion. Whether or not this would translate into economic viability cannot be assumed and is beyond the scope of this project.

3. CAPACITY OF STREAMFLOW FOR IRRIGATION EXPANSION IN THE CASS RIVER WATERSHED

3.1 Methods

Streamflow at 95, 90, 75 and 50 percent exceedence levels is used in this study to estimate the capacity of streamflow available for irrigation water supply. A computer program, BALANCE, was developed in this study to compute the amount of streamflow for irrigation and the maximum irrigation acreage that the streamflow can sustain.

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[34]The exceedence flow indicates the probability level at which streamflow is exceeded or equaled. For example, P_{75} = 57.4 cfs indicates that the streamflow would exceed or equal 57.4 cfs 75 percent of the time.

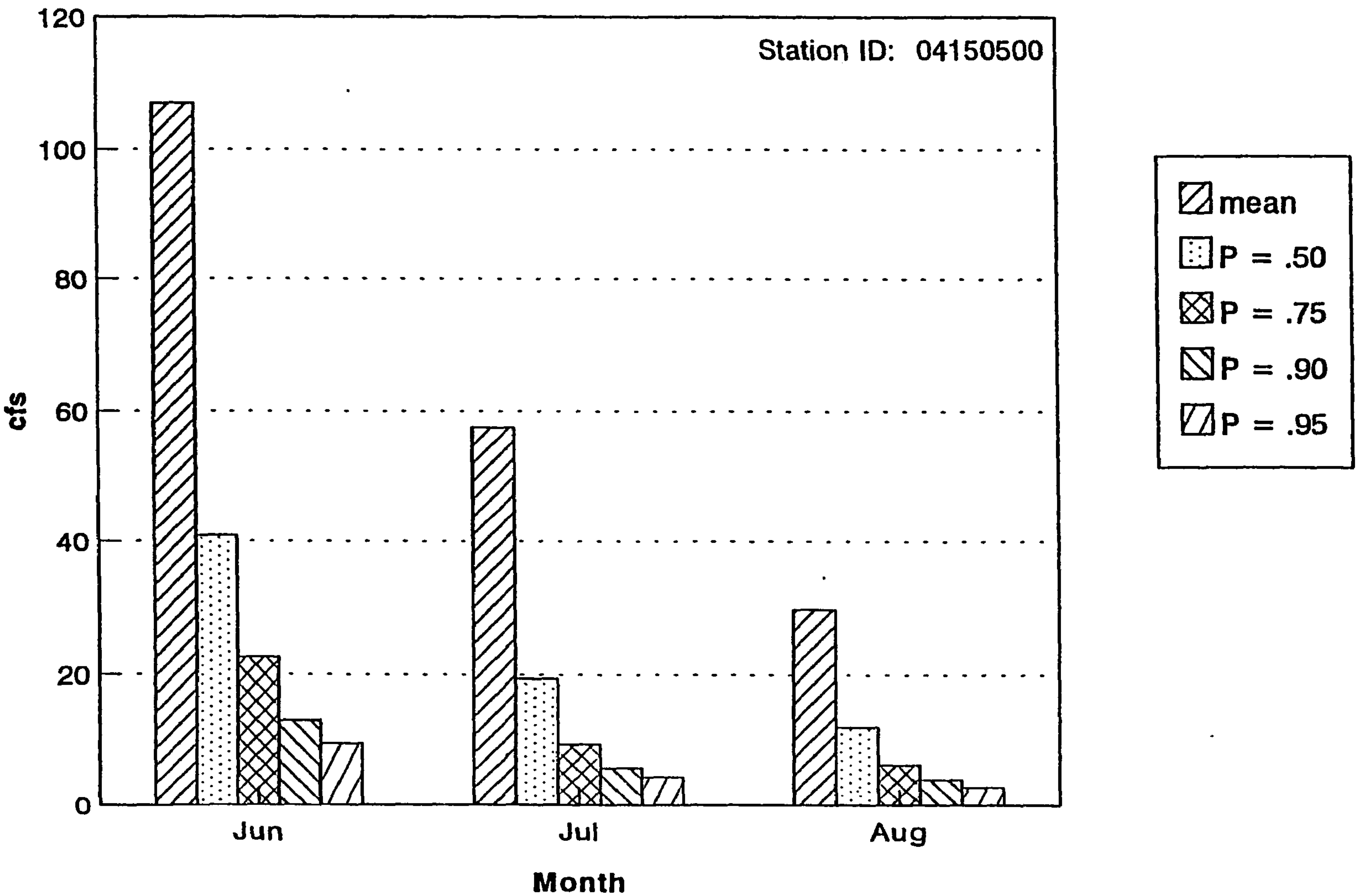

Figure 28. Exceedence Streamflow in the Cass River at the Cass City Station (1948-1985)

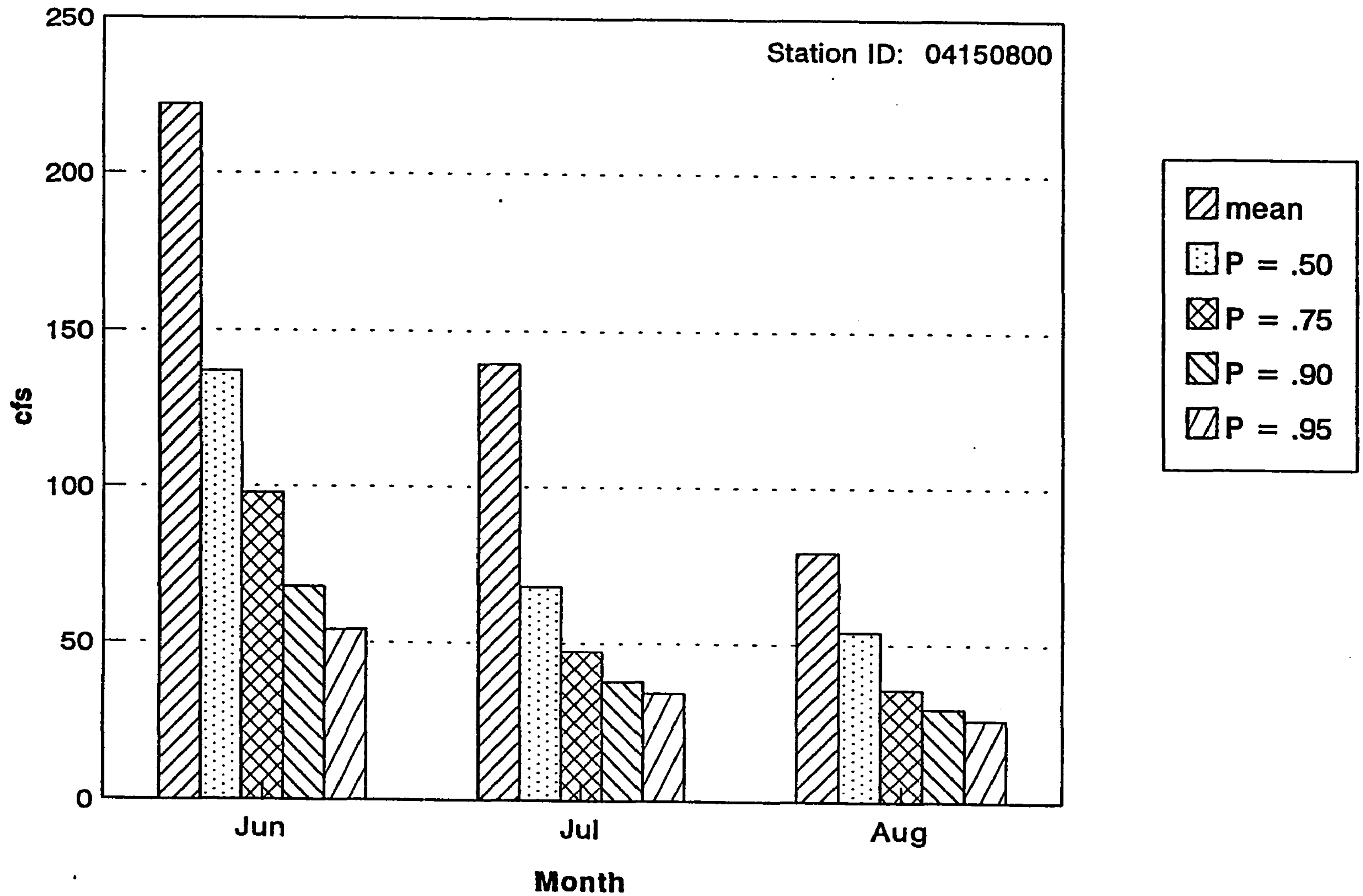

Figure 29. Exceedence Streamflow in the Cass River at the Wahjamega Station (1969-1985)

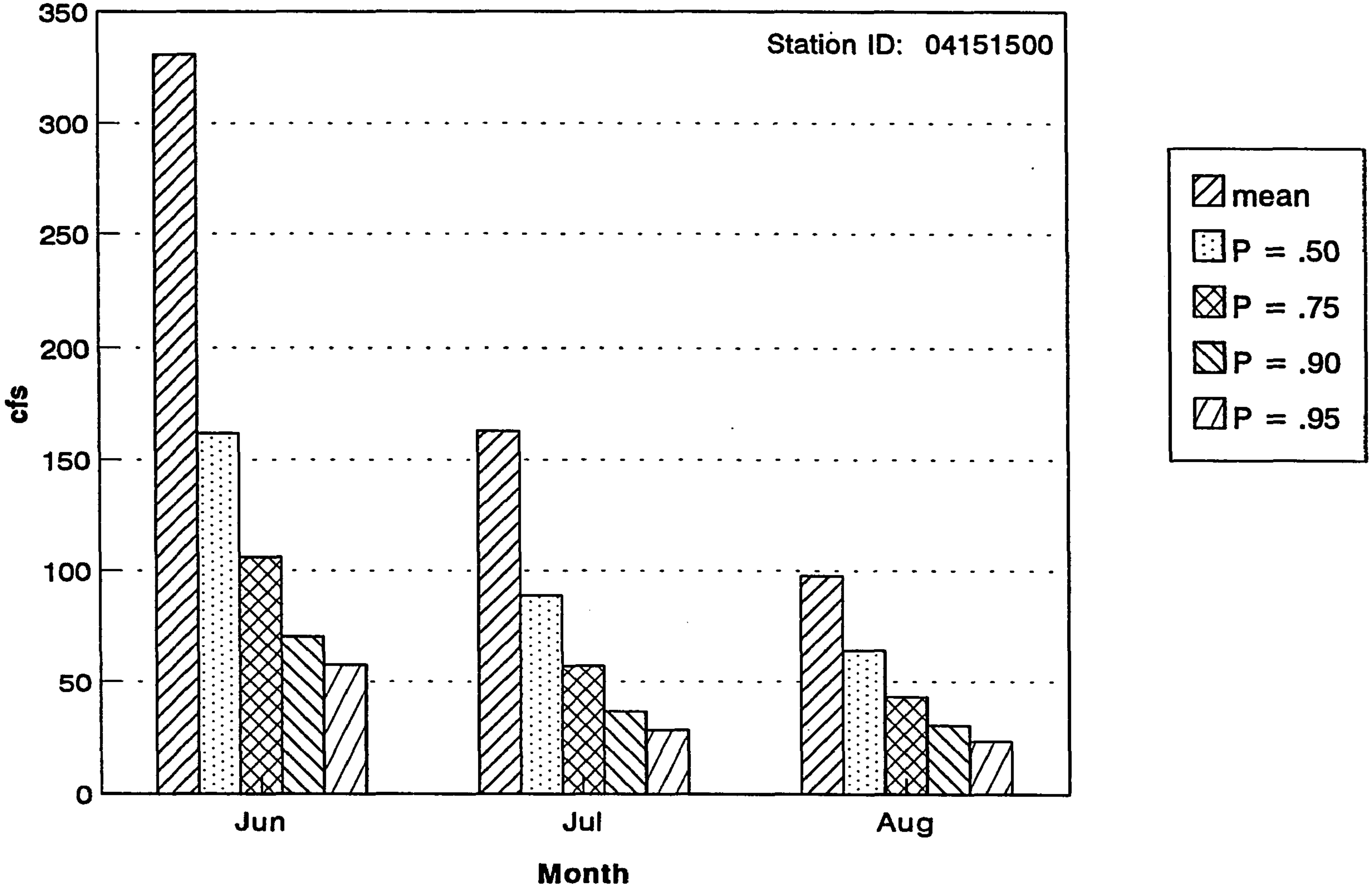

Figure 30. Exceedence Streamflow in the Cass River at the Frankenmuth Station (1936-1985)

Equations used in the program are described below:

$$V=\int_{T1}^{T2}(Q-Q_{95\%})\,dt \qquad (7)$$

where V = volume of water available for irrigation withdrawal in ft^3;

Q = streamflow in cubic feet per second (cfs) at an exceedence level;

$Q_{95\%}$=streamflow at 95 percent exceedence level in cfs; and

T_1, T_2 = starting and ending time in seconds, respectively.

It is assumed in Equation (7) that streamflow available for irrigation withdrawal is the amount of water above the 95 percent exceedence flow level set by the National Pollutant Discharge Elimination System (NPDES). The 95 percent exceedence flow is used for the NPDES program in setting effluent limits. It is used here as the lower threshold for the purpose of estimating the amount of water available for irrigation. It should be noted, however, that any withdrawals that would deplete the flow to the 95 percent exceedence level on a regular basis would seriously degrade the quality of the stream.

If water is withdrawn for irrigation upstream, the amount of water available downstream will be reduced. The amount of water for irrigation downstream is computed as follows:

$$V_d=\int_{T1}^{T2}(Q-Q_{95_t})\,dt-\int_{T1}^{T2}W_u dt \qquad (8)$$

where V_d = volume of water available for irrigation at the downstream location in ft^3; and

W_u = withdrawal rate at upper stream location(s) in cfs.

The irrigation requirements for corn, soybeans, dry beans, and sugarbeets are estimated by using the CERES-MAIZE, SOYGRO, BEANGRO, and YIELD models at a fixed irrigation efficiency of 75 percent. The total irrigation water requirement is computed by Equation (9).

$$V_i=1.43\int_{A1}^{A2} I\times E dA \qquad (9)$$

$$V_r=V-V_i \qquad (10)$$

where A = irrigation acreage, A_1 and A_2 are lower and upper limits of irrigation acreage, respectively;

I = irrigation water requirement in mm per acre, estimated by the simulation models;

E = irrigation efficiency (percentage);

V_i = volume of irrigation water requirement in ft^3;

V_r = volume of the remaining streamflow after irrigation withdrawal in ft^3; and

V = volume of streamflow before irrigation in ft^3.

The amount of streamflow available for irrigation is compared with the irrigation requirement in Equation (10). If the irrigation requirement is smaller than the streamflow supply, irrigation is expandable. Conversely, if the irrigation requirement is greater than the streamflow supply, the stream is unable to sustain the irrigation expansion. Irrigation expansion is thus limited by the maximum acreage that the stream can sustain. Attempts to expand irrigation beyond this limit would lead to streamflow depletion and fisheries habitat destruction.

3.2 Maximum Irrigation Acreage in the Cass River Watershed

As shown by Table 10, a minimum streamflow of 2,000 cfs is needed to irrigate all 392,713 acres of the total agricultural land (assuming it is planted only in sugarbeets) in July at a confidence level of 75 percent. Streamflow during the same period at the Frankenmuth gage station is only 57.4 cfs at the 75 percent exceedence level (Figure 27), which is far less than the total irrigation requirement of 2,000 cfs. This indicates that streamflow can only irrigate a small portion of the total agricultural land in the Cass River Watershed, especially if it is planted with crops that have greater irrigation requirements.

To compute the maximum irrigation acreage that the streamflow can support without depleting the stream, the irrigation requirements of corn (the major crop in the region) in July and August at the 75th percentile, and exceedence streamflow rates at the 50, 75, 90 and 95 percent levels, were entered into the BALANCE model. The simulation was run for the Cass City, Wahjamega, and Frankenmuth gage stations. The results are shown in Table 18.

It should be noted that the Frankenmuth gage station is located at the mouth of the Cass River. Streamflow at this station includes the contribution of the upper and middle drainage areas (i.e. Cass City and Wahjamega). Thus, the maximum irrigation acreage derived at the Frankenmuth station represents the total irrigation acreage that the entire Cass River can sustain.

Table 18. Maximum Irrigation Acreage Supported by Cass River Streamflow (Based on Irrigation Requirements of Corn at the 75th Percentile)

Location	Exceedence Flow in July			Exceedence Flow in August		
	P_{50}	P_{75}	P_{90}	P_{50}	P_{75}	P_{90}
Cass City	2,600	885	243	2,420	910	310
Wahjamega	5,920	2,310	640	7,310	2,500	910
Frankenmuth	10,520	5,030	1,460	10,620	5,130	1,850

*Assuming an irrigation efficiency of 75%

The maximum irrigation acreage for the entire irrigation season at an exceedence flow level is determined by choosing the minimum value between maximum July and August irrigation acreage, i.e., max A = min (Max A_7, Max A_8). The results show that, given an irrigation efficiency of 75 percent, the maximum irrigation acreage that the Cass River can support at the exceedence flow of 75 percent, without falling below the NPDES 95 percent exceedence flow limit, is 5,030 acres, which accounts for only 1.3 percent of the total agricultural land.[35] Irrigation could expand to 10,520 acres at an exceedence flow of 50 percent. If the upper stream portion of the watershed (the Cass City gage station) is evaluated separately, at the 75 percent exceedence flow level, it is capable of supplying water to only 885 acres of corn while maintaining a minimum 95 percent exceedence flow in the upper stream. If, at the same time, the middle stream (at the Wahjamega station) and the lower stream (at the Frankenmuth station) are being used for maximum irrigation, they can sustain 1,420 and 2,720 acres of irrigated corn, respectively.

It should be noted that the maximum irrigation acreage shown in Table 18 is derived by assuming that the streamflow is withdrawn down to the 95 percent exceedence level. If a higher exceedence flow level (e.g., 90%) was set, then even fewer acres could be irrigated.

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[35]Note that this estimate rests on the assumption that all available agricultural land is planted in corn. Any combination of the four major crops will further reduce irrigable acreage.

4. MAXIMUM IRRIGATION ACREAGE IN THE SAGINAW BAY AREA

The maximum acreage of corn (the major crop) that can be supported by streamflow irrigation in other major watersheds (Figure 31) in the Saginaw Bay area was computed the same way as that shown above for the Cass River Watershed. The results are shown in Table 19. The total irrigation requirement for each of the watersheds was derived by multiplying the acreage of total agricultural land in each watershed by the July irrigation water requirement of corn at the 75th percentile. If all 2 million acres of currently existing agricultural land were irrigated and planted in corn, a total streamflow of 11,362 cfs in all watersheds would be needed in July in order to meet the irrigation requirement. While assuming available streamflow for irrigation is the volume of water above the NPDES 95 percent exceedence flow level, the maximum acreage of land irrigable by streamflow in all gaged watersheds totals about 44,000 acres (assuming all acreage is in corn). This accounts for only about 2 percent of the total agricultural land in the Saginaw Bay five-county area.

It should be noted that agricultural irrigation is subject to the Riparian Rights Doctrine. This doctrine grants a riparian (i.e. landowner of property adjacent to a water body) the right to a reasonable use of that water on riparian land. However, one cannot interfere with another riparian's right of reasonable use including activities

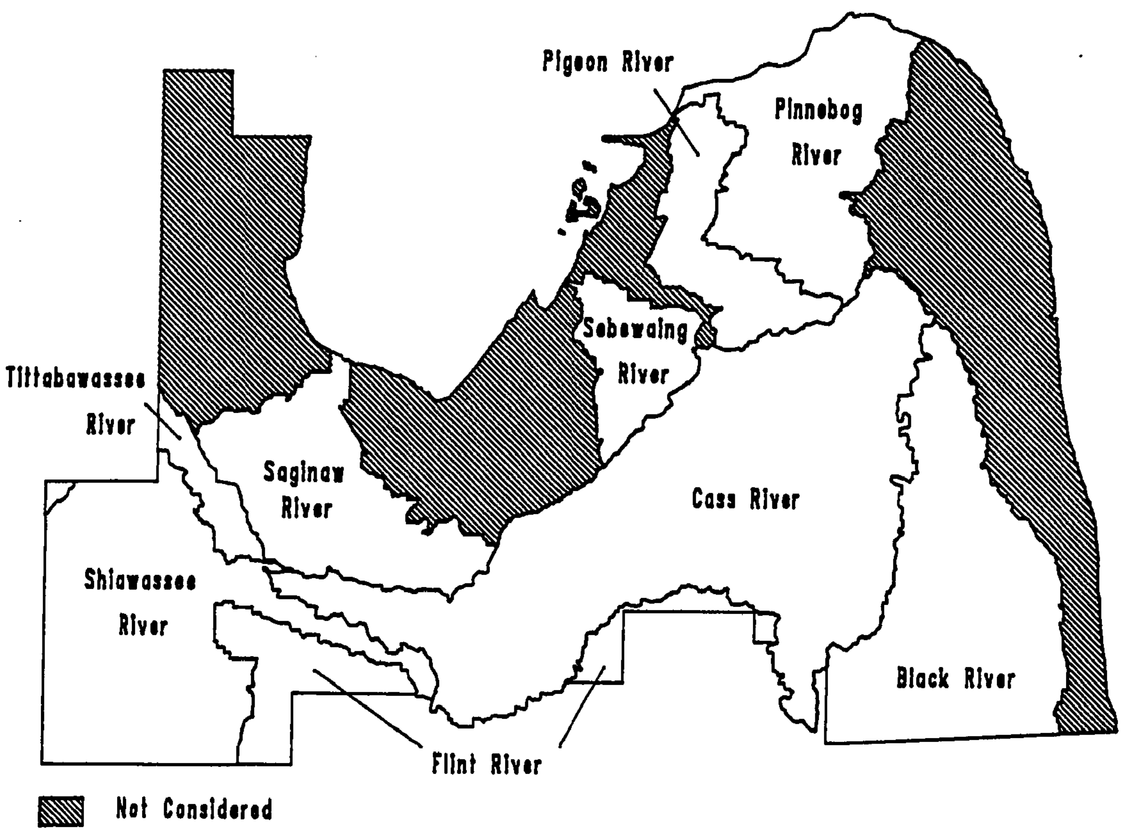


Figure 31. Watersheds in the Saginaw Bay Area

ranging from non-consumptive navigational and aesthetic uses to water supply and heavily consumptive agricultural irrigation. According to this doctrine, only riparian lands in the Saginaw Bay five-county area have a right to the use of streamflow for irrigation, and that right is limited to a reasonable use. That is, use of streamflow for riparian land irrigation should not adversely impact uses of the streamflow for other activities such as aesthetic enjoyment and maintenance of the ecosystem.

Table 19. Maximum Irrigation Acreage Supported by July 75 Percent Exceedence Streamflow in the Saginaw Bay Area (Based on the July Irrigation Requirement of Corn at the 75th Percentile)

Watershed	Ag. Land (Acres)	Irrig Demand (cfs)	Avail. Flow for Irrig. (cfs)	Maximum Irrig Land (acres)
Black	215,373	1,241	8.5	1,475
Cass	392,713	2,263	29.0	5,030
Flint	60,488	348	64.0	11,120
Pigeon	76,111	439	2.1	360
Pinnebog	87,643	505	N.A.	N.A.
Saginaw	104,611	603	N.A.	N.A.
Sebewaing	60,927	351	N.A.	N.A.
Shiawassee	179,706	1,035	34.2	5,940
Tittabawassee	35,310	203	116.0	20,180
Others	759,051	4,374	N.A.	N.A.
Total	1,971,933	11,362		

*Note: N.A. means no streamflow data were available.

IV. SUMMARY

A framework was developed in this study for managing water resources for irrigation development in the Saginaw Bay area. Crop growth simulation models and Geographic Information Systems (GIS) were used in this study to simulate the yields and irrigation requirements for corn, soybeans, dry beans, and sugarbeets. A hydrologic budget equation, well log records, and partial chemistry data were used to evaluate the sustainability of groundwater and streamflow for irrigation in the Saginaw Bay five-county area. The results indicate that:

1. Irrigation may increase the yields of corn, soybeans, dry beans, and sugarbeets by a large margin over non-irrigated identical plantings in the Cass River Watershed. The requirement for irrigation water is greatest in July and at the mean level averages 77 mm (3.03 inches) for corn, 105 mm (4.13 inches) for soybeans, 102 mm (4.02 inches) for dry beans, and 69 mm (2.72 inches) for sugarbeets. The irrigation requirement in July at the 75th percentile averages 108 mm (4.25 inches) for corn, 140 mm (5.51 inches) for soybeans, 130 mm (5.12 inches) for dry beans, and 96 mm (3.78 inches) for sugarbeets.

2. A minimum flow of 2,000 cfs is needed to satisfy the irrigation requirement if all 392,713 acres of agricultural land in the Cass River Watershed were irrigated for sugarbeet production (the least water-consumptive of the

crop alternatives). If all 2 million acres of the currently existing agricultural land in the Saginaw Bay five-county area were irrigated and planted with corn (the major crop in the region), a minimum flow of 11,400 cfs in all watersheds would be needed in July to meet the irrigation requirement.

3. Annual groundwater recharge from precipitation less surface runoff and evapotranspiration ranges between 2 to 4.6 inches. The annual baseflow resulting from discharges from the groundwater storage varies between 4.3 and 6.0 inches. The negative differences between recharge and baseflow indicate depletion of groundwater storage. They may also indicate upward movement of groundwater from bedrock aquifers, such as artesian wells reported by Allen (1974). Uncertainty associated with the estimates of annual ET could affect the estimates of recharge and groundwater storage change.

4. Central Huron County, western Sanilac County, and eastern Tuscola County may be recharge areas based on well yields, water quality and hydraulic heads of aquifers.

5. Total dissolved solids concentrations and salinity levels (indicated by chloride and sodium concentrations) are lower in the potential recharge areas in these counties.

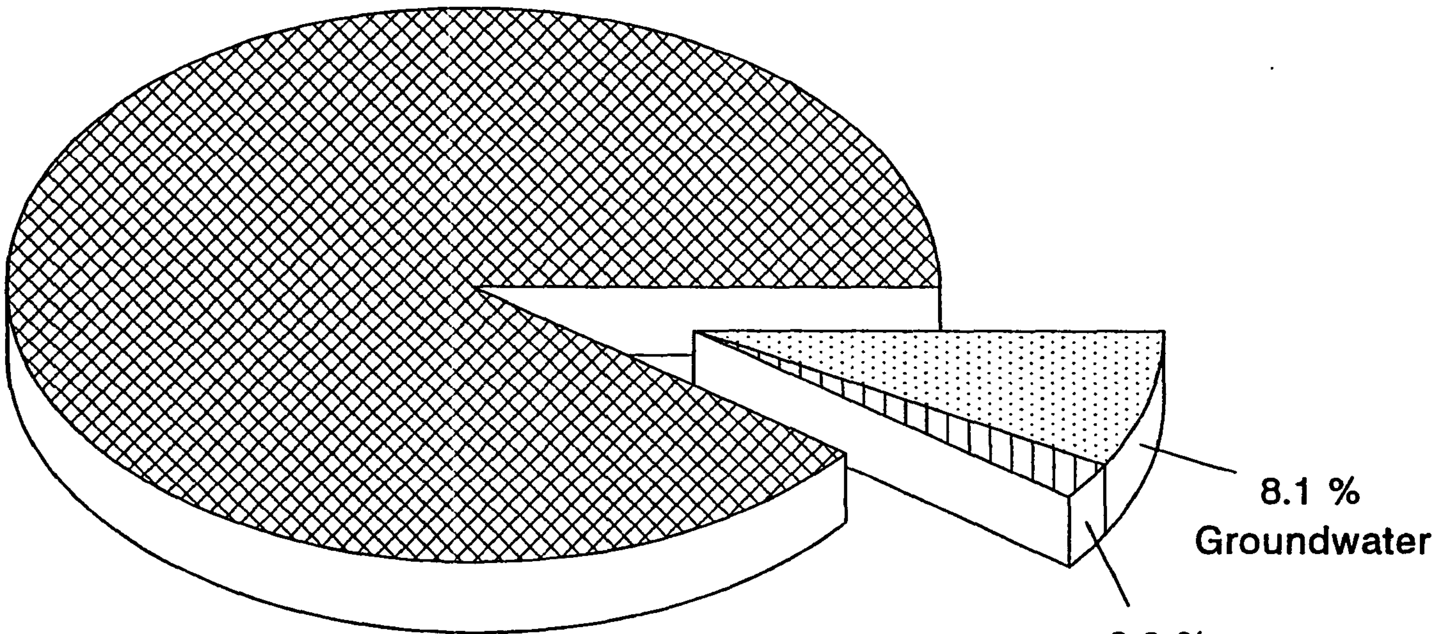
6. The Marshall Formation in the Saginaw Bay area is a source of water suitable for irrigation and domestic use. The maximum irrigation acreage that might be supported with groundwater is 160,000 acres, which accounts for 8 percent

of the total agricultural land in the Saginaw Bay area. Potential subsurface irrigation expansion areas may lie in parts of central Huron County, southwestern Sanilac County, and northeastern Tuscola County.

7. Streamflow in the Cass River is lowest in July. Assuming that the stream is withdrawn down to the 95 percent exceedence level, the maximum irrigation acreage that the entire Cass River Watershed can sustain at the 75 percent exceedence flow level is 5,000 acres. This is approximately 1 percent of the total agricultural land in the watershed. The maximum irrigation acreage that the streamflow can support in all gaged watersheds in the Saginaw Bay five-county area totals 44,000 acres (assuming all acreage is in corn), which accounts for only 2 percent of the total agricultural land in the Saginaw Bay area. If a higher level was set as the lower threshold for estimating the amount of water available for irrigation, even fewer acres could be irrigated.

8. If available groundwater and streamflow are combined to supply irrigation, the maximum irrigation acreage might be as many as 200,000 acres, which is 10 percent of the total agricultural land in the Saginaw Bay five-county area (Figure 32). However, withdrawal of groundwater for irrigation should be practiced cautiously since continuous pumping of groundwater would decrease the discharge to streams and also induce the upward movement of brine from

Expressed as a percentage of total agricultural land



Total Agricultural Land = 1,971,933 acres

Figure 32. Maximum Irrigation Acreage Supported by Groundwater and Streamflow (Combined) in the Saginaw Bay Area

the deeper aquifers. Moreover, reduction in the groundwater discharge due to irrigation could lead to the degradation and depletion of streamflow and the destruction of fisheries habitats.

9. Agricultural irrigation is subject to the Riparian Rights Doctrine. Only owners of riparian lands (i.e. lands adjacent to a water body) have a right to the use of the water and that right is limited to a reasonable use. That is, withdrawal of streamflow for riparian land irrigation should not adversely impact uses of the streamflow for other activities such as wetland protection, maintenance of fisheries habitats, and aesthetic enjoyment.

10. Simulation models are useful tools in aiding management of water resources for irrigation development. However, limitations of these models should be recognized when the model outputs are used for decision making. Of the four simulation models used in this study, the CERES MAIZE produced relatively accurate estimates of the corn yield and irrigation water requirements when compared to the actual data. The simulated dry bean yields were poorly correlated with the actual yields. To improve the reliability of the simulated yields and irrigation water requirements, long term field experiments must be conducted to validate the simulation models.

CHAPTER 6

DEVELOPMENT OF OPTIMAL IRRIGATION SCENARIOS

1. INTRODUCTION

Streamflow in the Cass River at the 75 percent exceedence level can, at most, support only 1 percent of the total available agricultural land (392,713 acres) for irrigation in the entire watershed. The four major crops (i.e. corn, soybeans, dry beans, and sugarbeets) are competing for the use of the limited groundwater and streamflow available for irrigation. Decision makers must determine which crops to irrigate, where to irrigate, and how much land to irrigate. Ignorance on the part of individual growers could lead to water extraction plans that are unsustainable and damage the watershed. With better information, public decision makers can effectively deal with these complicated issues. This study uses optimization techniques to determine the optimal crop mixes in order to maximize the total economic returns of irrigation while meeting the constraints of resources and activities. The outputs of the optimization models provide information regarding which crops to irrigate, how many acres to irrigate, and which soil association(s) to irrigate.

2. OPTIMIZATION MODEL

Linear programming (LP) models were developed to generate irrigation scenarios. The LP model is of the following form:

$$Max f(X)=\sum_{i=1}^{74} c_i x_i \quad (11)$$

$$\sum_{j=1}^{16} a_{ij} x_i \leq b_j \quad (12)$$

$$x_i \geq 0 \quad (13)$$

where x_i is a set of decision variables, a_{ij} is the resource consumption coefficient for each decision variable, c_i is the objective coefficient for each decision variable, and b_j is a set of available resources. Equation (11) is the objective function, Equation (12) is a set of resource constraints, and Equation (13) represents the non-negative requirements of decision variables.

In this study, x_i represents acreage of non-irrigated and irrigated corn, soybeans, and dry beans in each of the 12 soil associations, and non-irrigated and irrigated sugarbeets in all soils. Model restrictions and data availability did not allow yield and irrigation requirement of sugarbeets to be linked to soil associations. Thus, there are 74 decision variables in the models (3 crops, 2 irrigation types (irrigated vs. non-irrigated), 12 soil associations, and irrigated and non-irrigated sugarbeets, yielding 3*2*12 + 2 = 74 variables).

a_{ij} represents the coefficient in constraint j of variable i. For example, 129 mm (5.08 inches) of water is needed in July at the 75th percentile (i.e. 75% confidence level) to irrigate an acre of corn in the Oakville-Plainfield-Spinks soil association (soil #40) (constraint 2 of variable 2, see Appendix B).

b_j represents the available resources. For example, the total agricultural land in the entire Cass River Watershed is 392,713 acres.

2.1 Objective Function

The objective function of the LP model in this study is to maximize expected gross margins. In this study, C represents expected gross margins[36] for each of the decision variables (Ferris, 1990). For irrigated corn in the Oakville-Plainfield-Spinks soil association (#40), for example, the gross margin at the 75 percent confidence level is $90.70 per acre of land. Gross margin in this study was calculated from the following equation:

Expected Gross Margins/acre

= Gross Returns/acre - Variable Costs/acre (14)

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[36]Gross margin equals the gross returns in excess of variable costs per acre.

where Gross Returns

= Prices/unit * yields/acre (simulated)

and Variable costs include variable cash expenses plus an allocation for returns to operating capital and unpaid labor (Ferris, 1991).

Two values for per unit prices (per bushel for corn and soybeans, per hundred weight (cwt) for dry beans, and per ton for sugarbeets) were used in Equation (14): seasonal average value and the 25th percentile value. Seasonal average value is the average of the prices at real value (1982 - 1984 price = 100) over the period of 1960-1990. Seasonal average crop prices for 1960-1990 are shown in Figure 33 (Ferris, 1991). Crop prices at the 25th percentile indicate that crop prices in a particular year would be greater than the specified prices 75 percent of the time. The 25th percentile values represent the crop prices during the worst years over the period of 1960 - 1990. The estimates of gross margins at the 25th percentile are lower than the average level, and hence are conservative and less subject to overstatement.

Seasonal prices and variable costs at real value (average values of prices and variable costs between 1982 and 1984 = 100) for non-irrigated corn, dry beans, soybeans and sugarbeets in Michigan were obtained from Ferris (1991) for the period from 1960-1990. Additional variable costs associated with subsurface irrigated corn, dry beans,

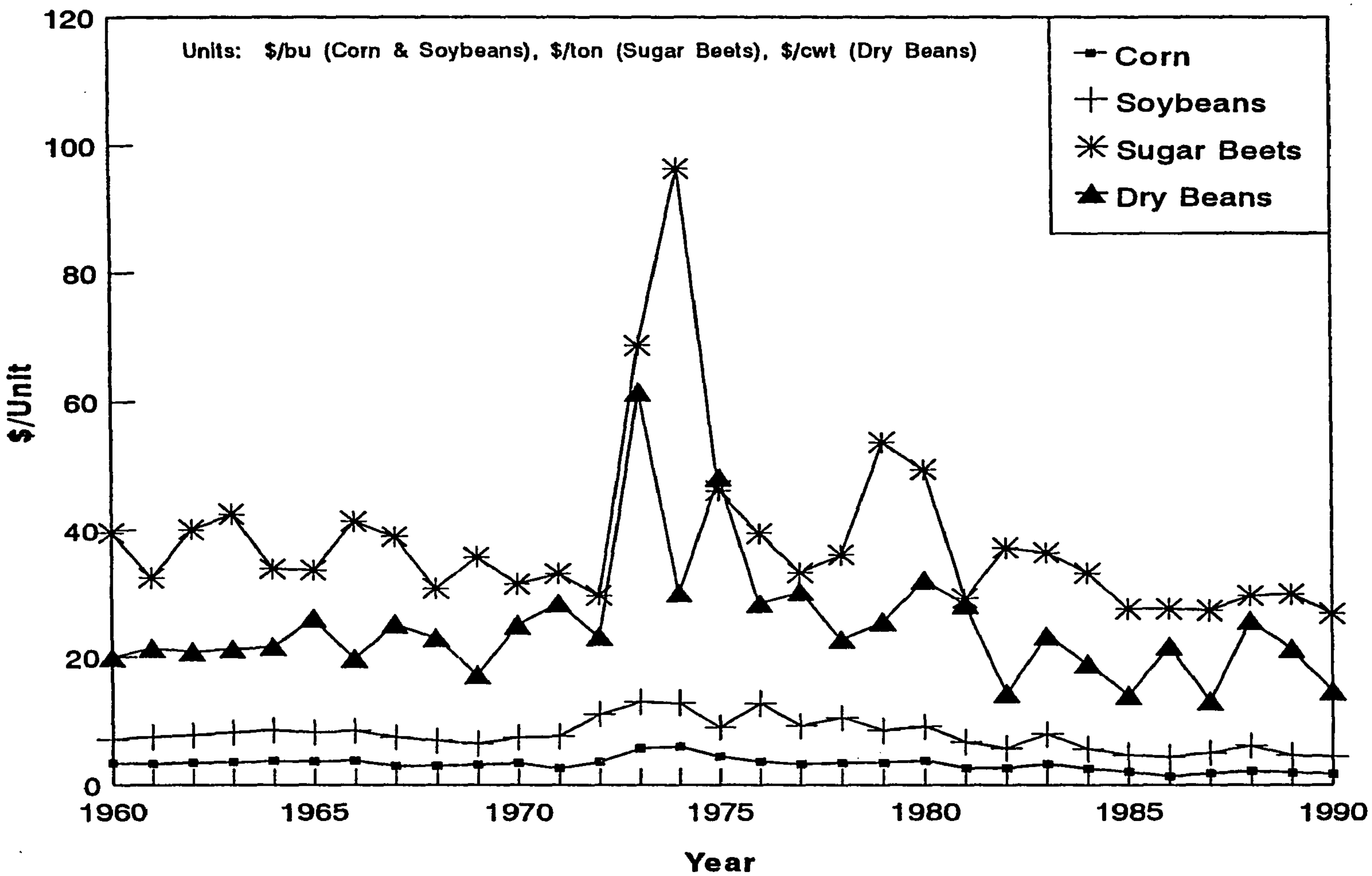

Figure 33. Seasonal Average Crop Prices in Michigan (Real Value, 1982-1984=100)
Source: J.W. Ferris, 1991. Michigan State University

soybeans and sugarbeets were obtained from LeCureux and Booms (1987, 1988a, 1988b).

2.2 Resource Constraints

The resource constraints considered in this study include:

1) Agricultural land acreage limit: the total acreage of crops shall not exceed the total acreage of the currently existing agricultural land.

2) Water resource constraint: the total requirement for irrigation shall not exceed the amount of streamflow available for irrigation at the 75 percent exceedence level. The available streamflow for irrigation was computed from the BALANCE model, assuming that it is the amount of water above the 95 percent exceedence flow level set by the NPDES (National Pollutant Discharge Elimination System). July was chosen as the critical period for irrigation since irrigation demand is greatest in July when streamflow is lowest.

3) Agricultural land constraint in each of the 12 soil associations: the total acreage of crops in each soil association shall not exceed the total acreage of each soil association. The agricultural land acreage in each of the 12 soil associations was derived by superimposing the land use map on the soil association map using ARC/INFO, a Geographic Information System (GIS).

4) Current crop mix constraint: the total acreage of sugarbeets shall not exceed the contract acreage set by the processing capacity of the sugar manufacturing companies. Acreage of dry beans has been declining since 1970s and may stay at the current level to keep the balance of the current crop production system.

Two LP models were developed in this study-- one with the model parameters at the mean level and the other with the model parameters at the 75 percent confidence level. The LP model for the Cass River Watershed crop mix at the 75 percent confidence level is listed in Appendix B.

3. RESULTS AND DISCUSSIONS

3.1 LP Model Outputs with Streamflow at the 75 and 50 Percent Exceedence Levels

The two LP models were run on the IBM 3090 (a mainframe computer) using LINDO (Linear, INteractive, and Discrete Optimizer) which is an interactive linear, quadratic, and integer programming system (Schrage, 1989). The outputs are listed in Appendices C and D. Tables 20 and 21 show the output summary. Spatial distribution of the outputs is shown in Figures 34 and 35.

Table 20. Output Summary of the LP Model with the Parameters at 75 Percent Confidence Level

Soil Association	Corn (acres)		Soybeans (acres)		Dry Beans (acres)		Sugarbeets (acres)	
	Irrig.	NonIr.	Irrig.	NonIr.	Irrig.	NonIr.	Irrig.	NonIr.
40		18,185			4,181			
41		84,910						
42		46,328				37,833		
43						20,713		
46		24,506						
48						4,034		
51		4,548						39,271
64		57,902						
69		16,191						
70		16,274						
73		14,939						
74		2,898						
Total		286,681			4,181	62,580		39,271

* Objective Function Value (Expected Gross Margins) = $40,197,504 (Prices and simulated yields are all at the 75 percent probability level)

Table 21. Output Summary of the LP Model with All the Parameters at Mean Level

Soil Association	Corn (acres)		Soybeans (acres)		Dry Beans (acres)		Sugarbeets (acres)	
	Irrig.	NonIr.	Irrig.	NonIr.	Irrig.	NonIr.	Irrig.	NonIr.
40		11,550			10,816			
41		74,184				10,726		
42		84,161						
43						20,713		
46						24,506		
48		4,034						
51		4,548						39,271
64		57,902						
69		16,191						
70		16,274						
73		14,939						
74		2,898						
Total		286,681			10,816	55,945		39,271

* Objective Function Value (Expected Gross Margins) = $139,375,280 (Prices and simulated yields are all average values)

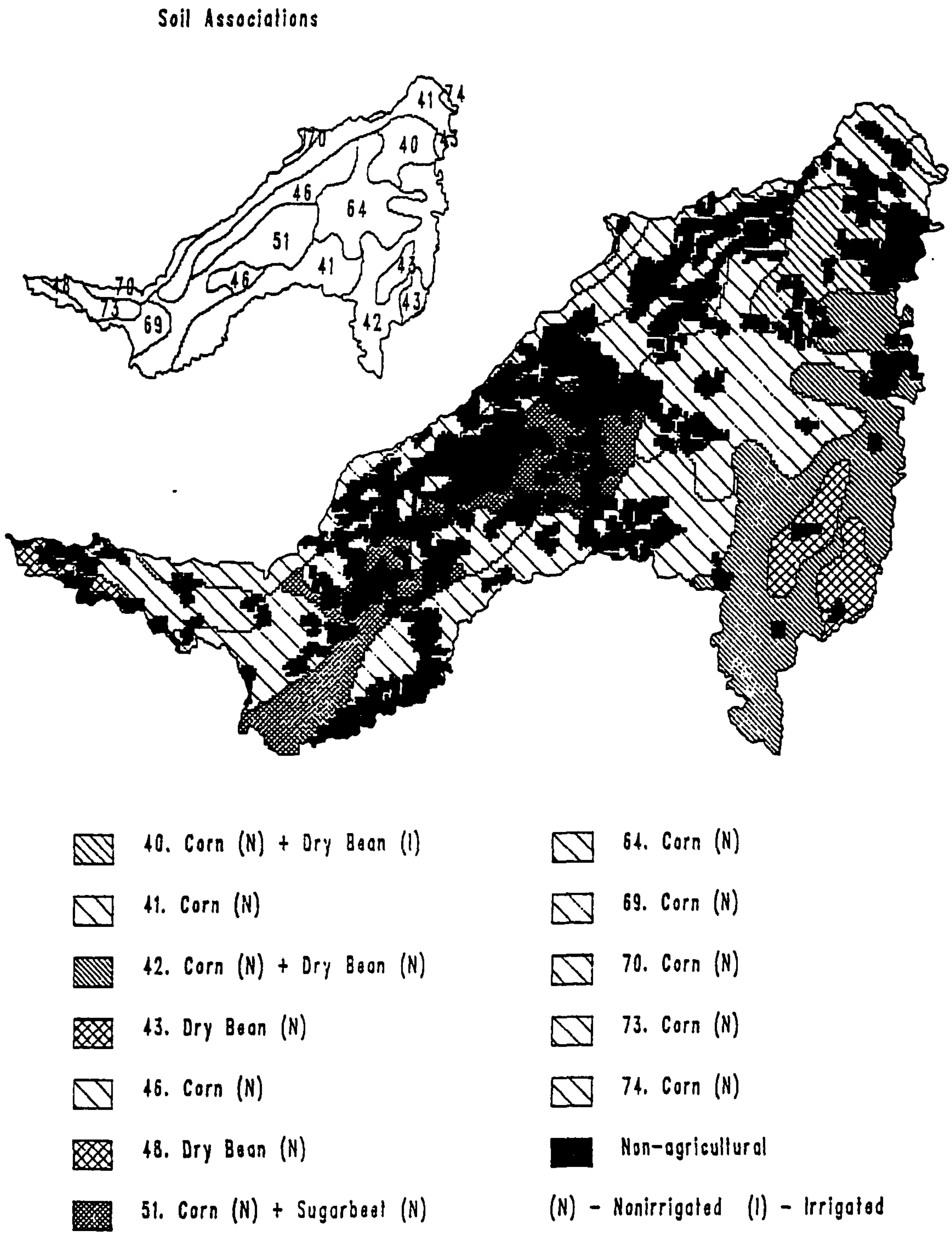

Figure 34. Spatial Distribution of the LP Model Output with the Parameters at 75 Percent Confidence Level

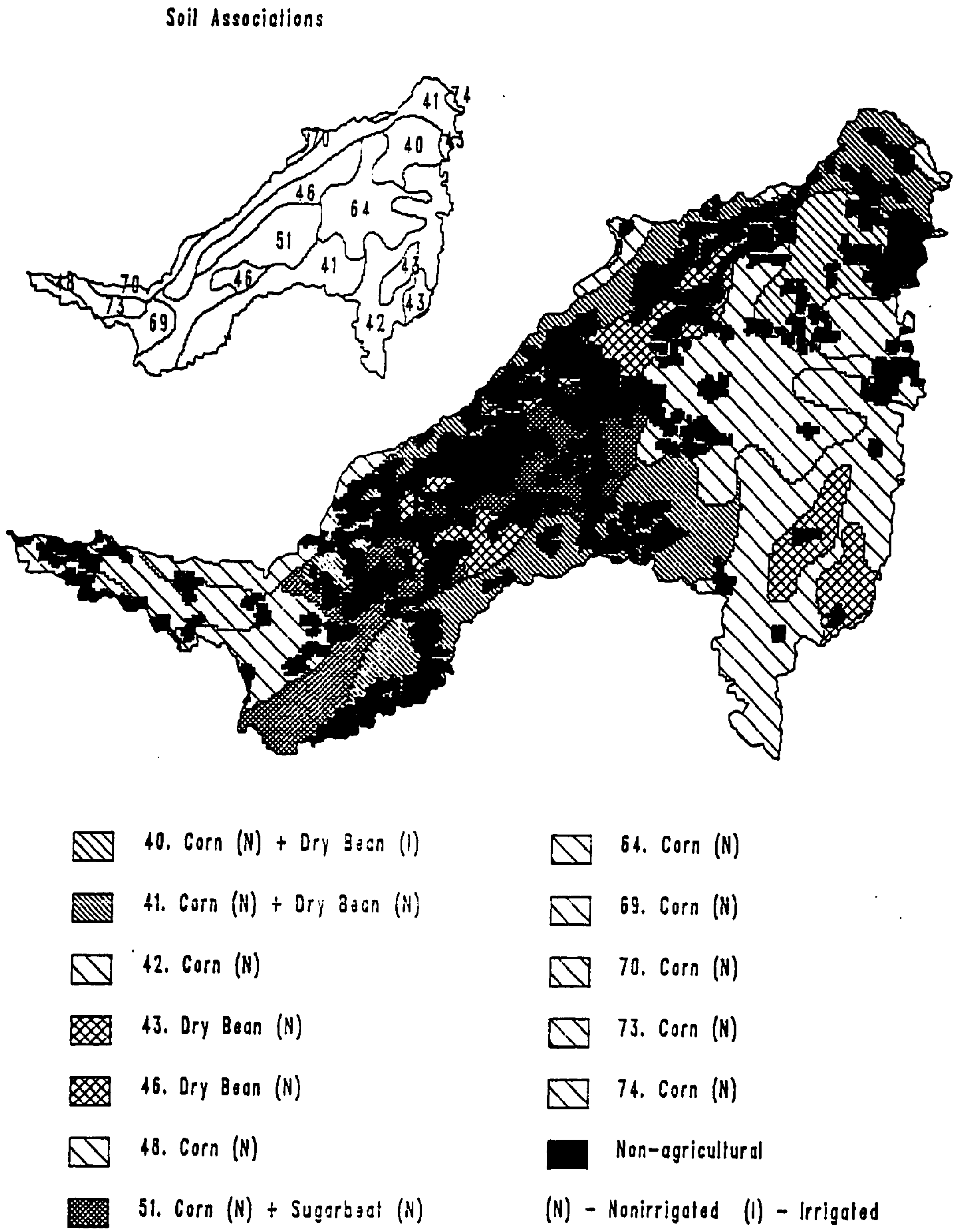

Figure 35. Spatial Distribution of the LP Model Output with the Parameters at Mean Level

As shown in Tables 20 and 21, and Figures 34 and 35, the model outputs indicate that the acreage of corn may be expanded to 286,681 acres, which accounts for 73 percent of the total agricultural land in the Cass River Watershed. Sugarbeets are limited to 39,271 acres by the sugar manufacturing companies' processing capacity. Irrigation priority may be given to dry beans in the Oakville-Plainfield-Spinks soil association (#40). At the 75 percent exceedence level, streamflow in the Cass River in July may irrigate 4,181 acres of dry beans. Total expected gross margins (similar to net income but do not subtract fixed costs such as taxes and interests) of the four crops in the entire watershed is up to $40,197,504, with a confidence level of 75 percent.

At the 50 percent exceedence level, streamflow in the Cass River can irrigate 10,816 acres of dry beans (with irrigation water requirements all at the mean level over the period of 1951-1980)(Table 21). Total expected gross margins of the four crops in the watershed may reach $139,375,280 (note that crop prices, variable costs, and simulated yields are all average values over the 30 year period), a 247 percent increase over the total expected gross margins at the 75 percent confidence level. The confidence level for the expected gross margins, however, is only 50 percent.

All the soybean variables were dropped out in the model outputs due to their low objective function coefficients (low gross margins per acre of land).

3.2 Sensitivity Analysis of the Model Output with the Streamflow at the 75 Percent Exceedence Level

The solution of the LP model with the streamflow at the 75 percent exceedence level is listed in Appendix C and Table 20. Appendix C also lists information on the sensitivity of the solution to the model, which is the impact of changing the value of a parameter (one at a time) on the solution of the model. This section discusses the amount that a parameter must change before the optimal solution changes.

As shown in Appendix C, if the optimal variable value is zero, the reduced cost is the amount that variable's objective function coefficient must improve before it is worthwhile for that variable to become positive. In the optimal solution of the model the values of all the soybean variables are zero. The reduced cost of these variables ranges from $12.44 to $824.76, which indicates that the objective function coefficient (gross margins per acre) of one of the soybean variables (changing one parameter at a time) must increase by the minimum amount of $12.44 to $824.76 in order to make the soybean variables positive. That is, assuming the unchanged price, the simulated soybean yields must increase by a large amount to make up the needed additional gross margin in order to make the soybean variables a favorable choice.

The dual price of a constraint in Appendix C is the objective function value's rate of improvement due to per unit change in its right hand side constraint, given that the set of positive variables does not change. The dual prices for Rows 3, 4 and 17 (constraints of streamflow, sugarbeet acreage and dry bean acreage) are $4.47, $401.37 and $126.30, respectively, which indicates that if streamflow available for irrigation is increased by one acre-mm (acre-millimeter), the gross margins of crops would be increased by $4.47. Similarly, if acreage of sugarbeets (dry beans) is expanded by one more acre, the gross margins of crops would be increased by $401.37 ($126.30).

The maximum allowable increase for streamflow is 2,364,090 acre-mms. That is, the available streamflow for irrigation can be increased from the current amount of 543,489 acre-mms to 2,907,579 acre-mms (an increase of 435%) without changing the current optimal solution basis. If change in the streamflow constraint exceeds the allowable range, the current optimal solution would be changed and the model needs to be re-run to obtain a new optimal solution. The maximum allowable increase for sugarbeet acreage is 4,548 acres, an increase of 11.6 percent (46,327 acres for dry beans, an increase of 69 percent). These changes, if within the allowable range, would not alter the optimal solution basis if they take place one at a time. Otherwise, the optimal solution basis would be changed and the model needs to be re-run.

The dual price of agricultural land constraint is -$49.55, indicating that if agricultural land is increased by one more acre, the objective function value (gross margin) would be reduced by $49.55. This is because the equality constraint requires that all the agricultural land be planted in crops including some crops such as non-irrigated corn in soil association #40 (CORN40NO) which have a negative gross margin. If the equality constraint is changed to "smaller than (<)" constraint, the optimal solution would be different and the dual price of the agricultural land constraint would become positive.

3.3 Verification of the LP Model Output with Streamflow at the 75 Percent Exceedence Level

The objective function coefficients (gross margins) in the two LP models were derived by multiplying simulated yields by crop prices and then subtracting variable costs per acre of land (see Equation 14). To verify the model output, a new LP model was developed (see Appendix F), which used actual non-irrigated crop yields at the 25th percentile in Tuscola County and actual irrigated crop yields in Huron County to derive the objective function coefficients. Four constraints used in the model include agricultural land acreage, streamflow at the 75 percent exceedence level, and sugarbeet and dry bean acreage limits. It was not possible to link the crop yields to the soil associations due to the availability of crop data. Summary of the model output is listed in Table 22.

The model output, given the assumptions of linearity and uniformity employed in the study, indicates the optimal crop mix as: corn, 73 percent; sugarbeets, 10 percent; and dry beans, 17 percent. Soybean variables were dropped out in the solution due to their low gross margins per acre of land. This result is essentially the same as the result obtained from the first LP model which used simulated crop yields to derive model parameters.

The reduced cost of non-irrigated and irrigated soybeans is $32.85 and $227.76, respectively, which indicates that the objective function coefficient (gross margins) of non-irrigated soybeans must increase by a minimum amount of $32.85 ($227.76 for irrigated soybeans) in order to make the non-irrigated soybean variable (irrigated soybeans variable) positive. The dual price of the streamflow constraint is about $2.64, which suggests that if available streamflow increases by one acre-mm, the objective function value would increase by $2.64. The streamflow available for irrigation may be increased by 846 percent without changing the optimal solution basis.

Table 22. Output Summary of the LP Model with Streamflow at 75 Percent Exceedence Level. The Objective Function Coefficients were derived from Actual Crop Yields in Tuscola and Huron Counties.

Variable	Acres
Non-irrigated corn	286,681
Irrigated corn	0
Non-irrigated soybeans	0
Irrigated soybeans	0
Non-irrigated dry beans	59,703
Irrigated dry beans	7,058
Non-irrigated sugarbeets	39,271
Irrigated Sugarbeets	0
Total	392,713

* Objective Function Value (Expected gross margins) =$27,322,832

The result of the LP model using actual crop yields agreed with the LP model output derived from the simulated crop yields. Thus, it is feasible to incorporate simulation models into optimization models to provide useful information for decision making.

3.4 LP Model Output with Unlimited Streamflow Supply

While assuming unlimited streamflow supply, the output of the LP model with crop prices and simulated yields all at the 75 percent confidence level shows that irrigable acreage in the Cass River Watershed is up to 372,000 acres, which is approximately 94.7 percent of the total agricultural land (Table 23, Figure 36, and Appendix E). The expected gross

Table 23. Output Summary of the LP Model with All the Parameter at 75 Percent Confidence Level (Assuming Unlimited Streamflow Supply)

Soil Association	Corn (acres)		Soybeans (acres)		Dry Beans (acres)		Sugarbeets (acres)	
	Irrig.	NonIr.	Irrig.	NonIr.	Irrig.	NonIr.	Irrig.	NonIr.
40							22,366	
41	4,142				63,863		16,905	
42	84,161							
43		20,713						
46	24,506							
48	4,034							
51	43,819							
64	57,902							
69	16,191							
70	16,274							
73	14,939							
74					2,898			
Total	265,968	20,713			66,761		39,271	

* Objective Function Value (Expected gross margins) = $132,945,120 (Prices and yields are all at the 75 percent confidence level)

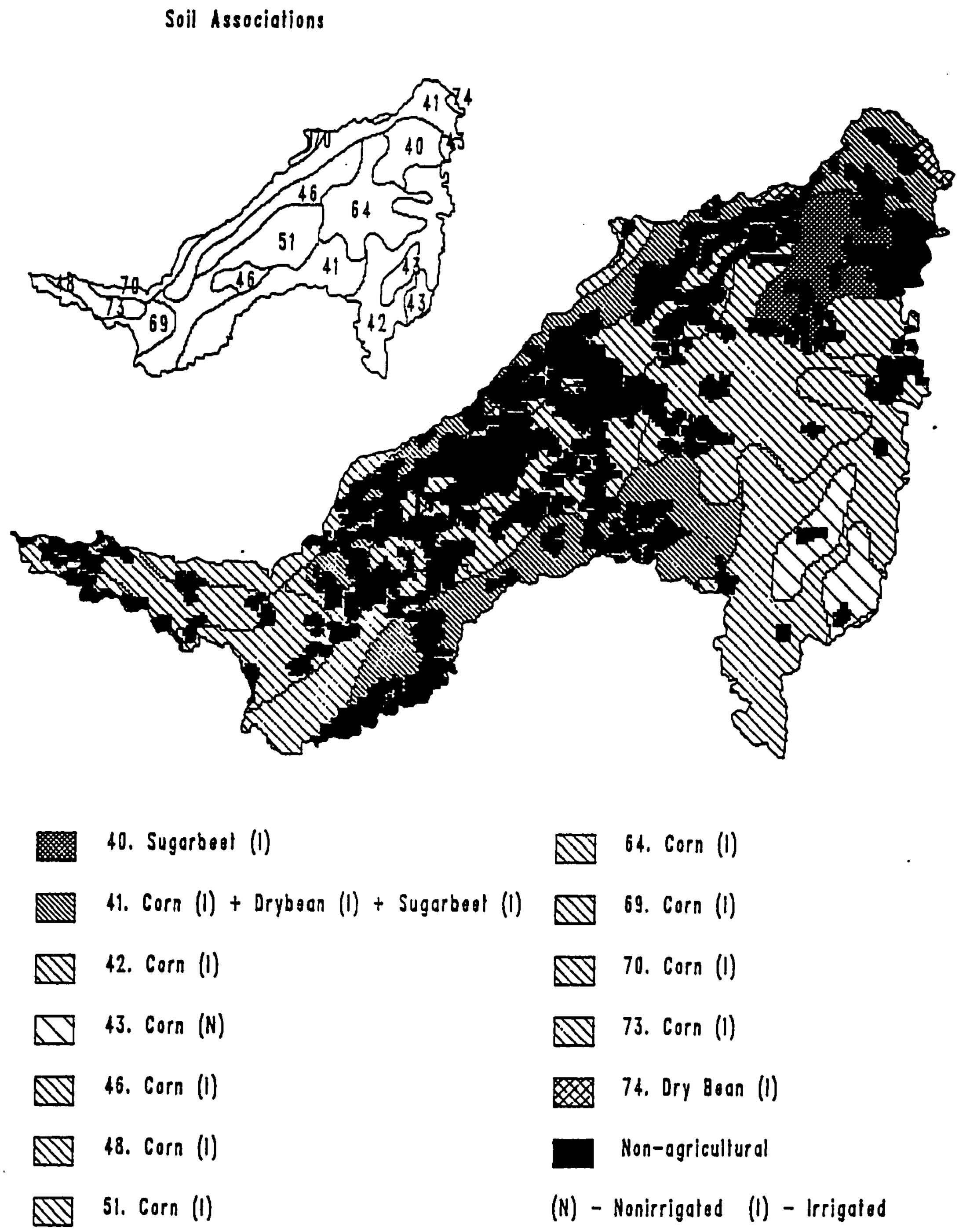

Figure 36. Spatial Distribution of the LP Model Output with the Parameters at 75 Percent Confidence Level, While Assuming Unlimited Streamflow Supply

margins of the four major crops reach $132,945,120, which triples the value produced with the Cass River streamflow at the 75 percent exceedence level. The non-irrigated 20,713 acres of agricultural land is in the Houghton-Palms-Sloan soil association (#43). This association is a mixture of organic and mineral soils and has a very high moisture content (Mokma,1991). The expected gross margin of simulated non-irrigated corn in this soil association is slightly higher ($5.56 per acre) than that of irrigated corn in the same soil. Thus, the LP model selected this soil for non-irrigated corn. This difference may need to be validated in future studies.

The model outputs dropped soybean production and expanded acreage for dry beans. This may be attributed to favorable dry bean prices. As shown by Tables 24 and 25, the actual gross margin of dry beans in Tuscola County from 1976 to 1980 averaged $248.82 per acre, whereas the actual gross margin of soybeans averaged $178.95 per acre. The difference between the two is about $70 (Ferris, 1991). In addition, the simulated dry bean yields are greater than the simulated soybean yields (per acre) and tend to increase the dry beans' gross margins. This indicates that (1) dry beans, especially irrigated dry beans, may have a greater production potential in the Cass River Watershed, and/or (2) the SOYGRO model under-estimated soybean yields, whereas the BEANGRO model seemed to over-estimate dry bean yields in the

Table 24. Soybean Gross Margins (Actual Yields in Tuscola County) (Prices and Variable Costs Comparable on the Basis of 1982-1984 Values = 100)

	Soybeans				
	Yield (bu/acre)	Price ($/bu)	Gross Return ($/acre)	Var. Cost ($/acre)	Gross Margin ($/acre)
1976	20.0	12.69	253.80	74.81	178.99
1977	31.0	9.14	283.34	76.91	206.43
1978	22.4	10.44	233.86	78.75	155.11
1979	27.2	8.44	229.57	87.46	142.11
1980	33.0	9.09	299.97	87.86	212.11
Average	26.7	9.96	260.11	81.16	178.95

Table 25. Dry Bean Gross Margins (Actual Yields in Tuscola County) (Prices and Variable Costs Comparable on the Basis of 1982-1984 Values = 100)

Year	Dry Beans				
	Yield (cwt/acre)	Price ($/cwt)	Gross Return ($/acre)	Var. Cost ($/acre)	Gross Margin ($/acre)
1976	9.5	28.30	268.85	86.02	182.83
1977	12.5	30.20	377.50	88.44	289.06
1978	10.8	22.70	245.16	90.56	154.60
1979	14.8	25.48	377.10	100.58	276.52
1980	13.8	32.04	442.15	101.04	341.11
Average	12.3	27.74	342.15	93.33	248.82

study area. These models need to be validated in the Saginaw Bay area to provide more accurate estimates of yields and irrigation water requirements for use in planning irrigation development.

3.5 Irrigation Expansion and Associated Risk

Expansion of irrigated acreage increases the expected gross margins of the crops. As Figure 37 shows, the greater the irrigated acreage, the higher the expected gross margins. However, irrigation expansion is inversely related to the exceedence level of streamflow (assuming streamflow is the only source for irrigation). The lower the streamflow exceedence (probability) level, the greater the irrigated acreage, and the higher the risk associated with the irrigation expansion (Figure 37). Expanding irrigated acreage at a higher streamflow exceedence level (probability) is likely to lead to the depletion of streamflow and the destruction of fisheries habitats. When making water use decisions, decision makers must take into account the reliability (exceedence flow levels) of streamflow for irrigation to avoid the aggregate impacts associated with irrigation expansion beyond sustainable levels.

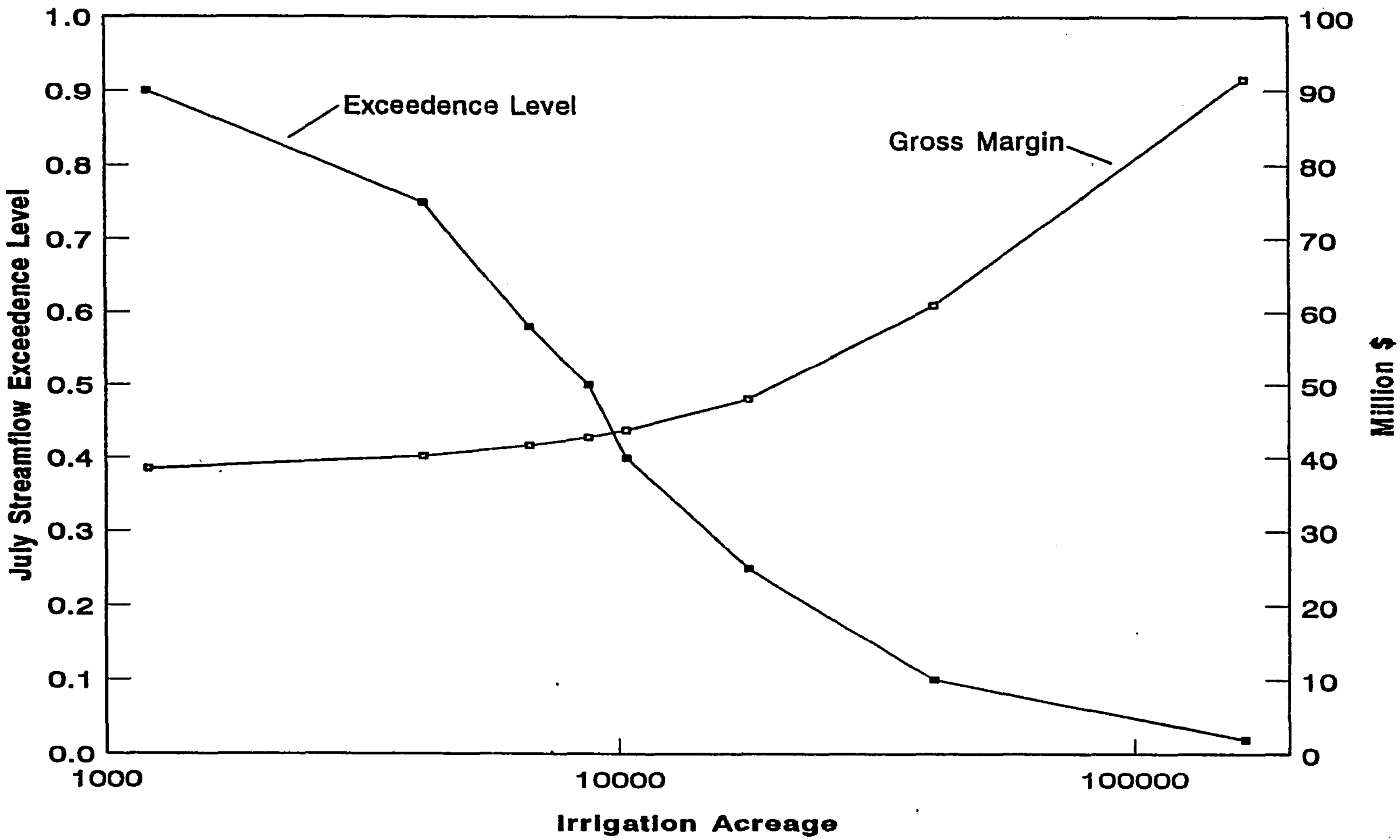

Figure 37. Expected Crop Gross Margins over a Range of Irrigation Acreage and Streamflow Exceedence Levels

4. SUMMARY

Use of optimization models in irrigation development can provide useful information for decision making. In this study three linear programming models were developed to derive information on optimal crop mixes and irrigation priority. The optimal solution indicates that acreage of corn may be expanded up to 73 percent of the total agricultural land in the Cass River Watershed. Soybeans may be dropped due to their low gross margin and low production potential per acre of land. The simulated results indicate that irrigation priority may be given to dry beans; the streamflow can irrigate approximately 4,200 acres of dry beans at the 75 percent exceedence level, or about 11,000 acres of dry beans at the 50 percent exceedence level. The availability of streamflow can be increased by 435 percent without changing the model solution basis. Results from the linear programming model using actual crop yields agreed with the above analysis. This information could be used for decision making if the simulated results are first validated in the study area.

Irrigation expansion is inversely related to the exceedence level of streamflow. The higher the probability of the exceedence flow, the lower the potential and the less the risk associated with irrigation expansion. If unlimited streamflow supply were available for irrigation, the expected gross margins of the four major crops in the Cass

River Watershed could reach 133 million dollars, which triples the expected gross margins with the Cass River streamflow at the 75 percent exceedence level. To accommodate an adequate water supply for irrigation in the study area, surface or aquifer storage of early spring streamflow or withdrawal of Lake Huron water might prove to be a promising alternative. These options need to be thoroughly examined before large investments are committed to irrigation expansion.

CHAPTER 7

SUMMARY AND CONCLUSIONS

1. SUMMARY

This study develops a framework for managing water resources using a case of irrigation development in the Saginaw Bay area of Michigan. The components of this framework include the: (1) estimation of crop irrigation water requirements, (2) evaluation of groundwater sustainability for irrigation, (3) assessment of streamflow capacity for irrigation, (4) optimization of expected irrigation returns, and (5) spatial distribution of irrigation development. Crop growth simulation models were used in this study to simulate yields and irrigation water requirements of corn, soybeans, dry beans, and sugarbeets. These models and the hydrologic budget equation as well as the optimization models were used to evaluate groundwater and streamflow available for irrigation, and to develop spatially oriented irrigation scenarios based on 30-year data on weather, streamflow, soil, and management practices in the Saginaw Bay five-county area. The results indicate that:

1. Irrigation may increase yields of corn, soybeans, dry beans and sugarbeets by a large margin over non-irrigated identical plantings in the Cass River Watershed. The requirement for irrigation water is greatest in July and at the mean level averages 77 mm (3.0 inches) for corn, 105 mm (4.1 inches) for soybeans, 102 mm (4.0 inches) for dry beans, and 69 mm (2.7 inches) for sugarbeets. Irrigation water requirements in July at the 75 percent confidence level average 108 mm (4.3 inches) for corn, 140 mm (5.5 inches) for soybeans, 130 mm (5.1 inches) for dry beans, and 96 mm (3.8 inches) for sugarbeets.

2. A minimum flow of 2,000 cfs is needed in July to satisfy the irrigation water requirement if all 392,713 acres of agricultural land in the Cass River Watershed were irrigated for sugarbeet production (the least water-consumptive of the crop alternatives). If all 2 million acres of the existing agricultural land in the Saginaw Bay five-county area were irrigated and planted in corn (the major crop in the region), a minimum flow of 11,400 cfs for all watersheds would be needed in July to meet the irrigation requirement.

3. Groundwater recharge due to precipitation less surface runoff and evapotranspiration ranges between 2 to 4.6 inches annually. The annual baseflow resulting from discharges from groundwater storage varies between 4.3 and 6.0 inches per year. The negative differences between

recharge and baseflow may indicate depletion of groundwater storage. They may also indicate the upward movement of groundwater from bedrock aquifers, such as occurs with artensian wells reported by Allen (1974). Errors in the annual ET estimates could affect the estimates of recharge and groundwater storage change by the hydrologic budget approach.

4. Central Huron County, western Sanilac County, and eastern Tuscola County may be recharge areas. Total dissolved solids concentrations and salinity levels (indicated by chloride and sodium concentrations) are lower in these potential recharge areas.

5. The Marshall Formation in the Saginaw Bay area may be the only source of water suitable for irrigation and domestic use. The maximum irrigation acreage that might be supported with groundwater is 160,000 acres, accounting for 8 percent of the total agricultural land in the Saginaw Bay area. Potential subsurface irrigation expansion by groundwater supply may lie in parts of central Huron County, southwestern Sanilac County, and northeastern Tuscola County.

6. Streamflow in the Cass River is lowest in July. Assuming the stream is withdrawn down to the 95 percent exceedence level, the maximum irrigation acreage that the entire Cass River Watershed can sustain at the 75 percent exceedence flow level is 5,000 acres, which is approximately

1 percent of the total agricultural land in the watershed. The maximum irrigation acreage that the streamflow can support in all gaged watersheds in the Saginaw Bay-five county area totals 44,000 acres (assuming all acreage is in corn), which accounts for only 2 percent of the total agricultural land in the Saginaw Bay area. If a higher level was set as the lower threshold for estimating the available amount of water for irrigation, even fewer acres could be irrigated.

7. If available groundwater and streamflow are combined to supply irrigation, the maximum irrigation acreage might be as many as 200,000 acres, which is 10 percent of the total agricultural land in the Saginaw Bay five-county area. However, use of groundwater for irrigation should be practiced cautiously since continuous pumping of groundwater would decrease the discharge to streams and also induce the upward movement of brine from the deep aquifers. Moreover, reduction in groundwater discharge due to irrigation could lead to the degradation and depletion of streamflow and to the destruction of the fisheries habitats.

8. Agricultural irrigation is subject to the Riparian Rights Doctrine. Only owners of riparian lands (i.e. lands adjacent to a water body) have a right to the use of the water and that right is limited to a reasonable use. That is, withdrawal of streamflow for riparian land irrigation should not adversely impact uses of the streamflow for other

activities, such as wetland protection, maintenance of fisheries habitat, and aesthetic enjoyment.

9. Optimal irrigation scenarios, given the assumptions of linearity and uniformity employed in this study, indicate that acreage of corn may be expanded to 73 percent of the total agricultural land in the Cass River Watershed. Soybeans may be dropped due to their low gross margin and low production potential per acre of land. The simulated results show that irrigation priority may be given to dry beans due to their greater expected gross margins per acre of land; the streamflow can irrigate 4,200 acres of dry beans at the 75 percent exceedence level or 11,000 acres of dry beans at the 50 percent exceedence level. The availability of water resources can be increased by 435 percent without changing the model solution basis (the optimal crop mix). The outputs from the linear programming model using actual crop yields agreed with these results. This information could be used for decision making only if the simulated results were to be first validated in the study area.

10. Irrigation expansion is inversely related to the exceedence level of the streamflow. The higher the probability of the exceedence flow, the lower the potential and the less the risk associated with irrigation expansion. If unlimited streamflow supply were available for irrigation, the expected gross margins of the four major

crops in the Cass River Watershed could reach 133 million dollars, which triples the expected gross margins with the Cass River streamflow at the 75 percent exceedence level. To accommodate an adequate water supply for irrigation in the study area, surface or aquifer storage of early spring streamflow or withdrawal of water from Lake Huron might prove to be a promising alternative. These options need to be thoroughly examined before large investments are committed to irrigation expansion.

11. Computer simulation and optimization models and Geographic Information Systems are useful tools in supporting decision making in water resource management. However, all simulation models have their limitations which must be recognized when the model outputs are used in the decision making process. In this study, errors with the estimates of irrigation requirements and yields ranged from 6-12 percent for corn, sugarbeets, and soybeans, and a higher percentage for dry beans when compared to the actual yields and the amount of irrigation applied to these crops. Of the four simulation models used in this study, the CERES MAIZE produced relatively accurate estimates of the corn yield (the major crop in the study area) and irrigation water requirements. To improve the accuracy of the simulated results and support effective decision making, long term field experiments (up to several decades) must be conducted to validate the simulation models.

2. CONCLUSIONS

Multiple demands have been placed on water for enhanced food production, industrial development, maintenance of the ecosystem, and aesthetic and recreational use. Management of the limited water resources for meeting these multiple demands is one of the important challenges facing decision makers and resource planners today. This study develops a framework to aid decision making in water resource management for irrigation development. The findings from this study reveal that the management of water resources for irrigation development can be significantly implemented by adopting systems approach (see definition on Page 6). The crop irrigation requirements, sustainability of water resources, economic returns and environmental impacts must be considered in irrigation planning to ensure the wise use of limited water resources.

Computer simulation models and GIS are useful tools in aiding management of water resources for irrigation development. However, models to be used in irrigation planning should have a sound physical basis and should have been first validated in the field. When using the models to estimate irrigation water requirements, the factors of weather, soils, crop genetics and management practices should be considered. This study used four simulation models to estimate the irrigation requirements and yields of corn, dry beans, soybeans and sugarbeets at the soil association level on a 30-year basis. The models produced satisfactory results for corn and sugarbeets but had substantial errors in estimating the yields and irrigation requirements of soybeans and dry beans. In order to provide reliable information in irrigation planning, long term field experiments which are beyond the scope of this study must be conducted in the Saginaw Bay area to validate the simulated results. This effort may well take few decades if detailed information is desired.

Evaluation of the available water resources for irrigation supply must consider the quantity and quality of both streamflow and groundwater. This study used the hydrologic budget approach to estimate the recharge, discharge and groundwater storage change rates in the study area. In addition, well log records and partial chemistry data were used to determine flow direction and water quality. The results indicate that use of groundwater for irrigation could lead to reduction in discharge to streams and may result in groundwater contamination due to induced upward movement of brines from the deeper aquifers.

Assessment of the capacity of streamflow for irrigation must consider the instream use of the flow which includes fish propagation, recreation and maintenance of wildlife habitat. This study assumed the amount of water above the 95 percent exceedence flow level set by the National Pollutant Discharge Elimination System (NPDES) as available water for irrigation supply. The results indicate that the available streamflow may be sufficient to supply a maximum acreage of 44,000 acres, which is only 2 percent of the total agricultural land in the study area. It should be noted, however, that any withdrawals that would deplete the flow to the 95 percent exceedence level on a regular basis would seriously degrade the quality of the stream.

Development of optimal crop mixes to maximize the expected economic returns of irrigation must consider land and water resource constraints as well as the current land use patterns. In addition, the parameters, including the crop prices in the optimization model, should be well established and documented. The optimization models developed in this study used parameters with 75 percent probability at the soil association level to derive the optimal crop mixes in the study area. Although the model results indicate that corn acreage may be expanded, this information must be validated before being used in support of decision making.

This study serves to illustrate relationships between multiple models and variables within them. It demonstrates how the models can be integrated together to address the complex relationships between crop irrigation requirements, availability of water resources and economic returns. It shows that, although the framework developed in this study can be expanded to multiple applications, field experiments are necessary to validate the input parameters which drive the models. Taken to its extreme, the results of the framework study suggest that, while it can be generalized and exported for use by decision makers, the acceptance or rejection of empirical validations must itself become one of the tasks of decision makers.

CHAPTER 8

RECOMMENDATIONS FOR FUTURE STUDIES

The development of a water resource management structure to evaluate the impacts of irrigation development in the Saginaw Bay area of Michigan is the central focus of this work. Crop simulation models were integrated with a hydrologic budget equation, optimization models and Geographic Information Systems to evaluate the availability of groundwater and streamflow for irrigation supply. The results indicate that the available streamflow and groundwater are unlikely to sustain the potential increases in demand for irrigation. For better refinement and validation of the model results, future studies on the following aspects are recommended:

1. Field experiments to validate the simulated irrigation requirements, yields and gross margins (economic returns) of corn, dry beans, soybeans and sugarbeets.

2. Hydrogeologic investigations in the Saginaw Bay area, particularly in Sanilac and Tuscola Counties to determine annual ET rate, recharge and discharge rates, locations of recharge areas, regional flow and upward leakage of groundwater from deeper aquifers.

3. Feasibility studies to assess social, economic, and environmental impacts of withdrawing water from Saginaw Bay of Lake Huron for irrigation water supply.

4. Economic impact studies to evaluate the regional effects of expanded subsurface irrigation on employment, income, processing facilities, manufacturing sectors, banking and insurance, and markets in the Saginaw Bay area and in the State of Michigan.

5. Social impact studies to identify who benefits from the expanded subsurface irrigation and how the benefits generated from the expanded irrigation are being distributed among the different groups in the region.

The development of subsurface irrigation in the Saginaw Bay area is a complex project and involves a broad range of social, economic, engineering and environmental issues. This study evaluates the water resource availability for irrigation expansion. The results indicate that groundwater and streamflow in the Saginaw Bay area are unlikely to sustain the potential increases in demand for irrigation. Withdrawing water from Saginaw Bay may be an alternative for irrigation supply. However, diversion of water from the Great Lakes basin is a very contentious issue. It is likely to involve both administrative and judicial offices in the region, state, and the country. There is a standing supreme committee to adjudicate the dispute over water diversion from the Chicago basin. Any attempt to divert water from the upper Great Lakes basin would be likely to encounter similar constraints. This study examines only a small part of the large institutional framework likely to be involved in the decision making process of irrigation planning. Thus, the results of this study should be reviewed within the context of the larger institutional structure. Although the framework developed in this study can be used to aid decision making, it is likely that it can be significantly improved in conjunction with other criteria which are well beyond the scope of this study. It is hoped that this study will provide a solid basis for subsequent analyses which will eventually allow a synthesis of the minimum necessary set of variables requisite for decision making on a regional scale.

APPENDIX A

Groundwater Recharge Rates Estimated by the Computer Program by Pettyjohn and Henning (1979)

RIVER	YEAR	DRAINAGE AREA (Sq.Mi.)	PRECIP. (In.)	LOCAL MINIMA	RECHARGE IN/YR INTERVAL DAYS	SLIDING INTERVAL	INTERVAL DAYS
Black near Fargo	1961	475	29.49	1.05	7	1.14	7
	1985	480	38.88	5.48	7	6.99	7
	1986	480	36.90	2.90	7	5.68	7
	1987	480	27.70	3.52	7	4.36	7
	1988	480	22.16	2.31	7	2.56	7
	1989	480	27.09	1.55	7	1.74	7
	Mean		30.37	2.80		3.75	
Cass at Frankenmuth	1961	848	27.27	2.14	7	2.24	7
	1985	841	36.26	6.35	7	7.62	7
	1986	841	41.81	7.07	7	6.66	7
	1987	841	28.05	5.20	7	5.14	7
	1988	841	29.53	3.60	7	3.77	7
	1989	841	28.89	3.41	7	3.68	7
	Mean		31.97	4.63		4.85	
Flint near Fosters	1961	1120	30.54	2.67	9	2.72	9
	1985	956	40.62	7.21	7	9.35	7
	1986	956	37.54	7.16	7	9.47	7
	1987	956	29.24	6.46	7	7.42	7
	1988	956	27.64	4.63	7	5.70	7
	1989	956	32.34	4.95	7	5.18	7
	Mean		32.99	5.51		6.64	
Pigeon near Owendale	1961	475	29.49	1.05	7	1.14	7
	1985	480	38.88	5.48	7	6.99	7
	1986	480	36.90	2.90	7	5.68	7
	1987	480	27.70	3.52	7	4.36	7
	1988	480	22.16	2.31	7	2.56	7
	1989	480	27.09	1.55	7	1.74	7
	Mean		30.37	2.80		3.75	
Shiawassee at Owosso	1961	538	27.50	3.29	7	3.38	7
	1985	538	41.16	6.68	7	7.76	7
	1986	538	41.89	5.92	7	7.74	7
	1987	538	32.83	4.88	7	6.18	7
	1988	538	*	4.40	7	5.23	7
	1989	538	31.53	7.17	7	7.48	7
	Mean		34.98	5.39		6.30	
Tittabawassee at Midland	1961	2400	31.60	3.08		3.22	9
	1985	2400	35.53	4.50	9	4.75	9
	1986	2400	39.52	5.54	9	5.80	9
	1987	2400	27.08	3.99	9	4.15	9
	1988	2400	31.80	3.51	9	3.72	9
	1989	2400	24.45	3.74	9	4.22	9
	Mean		31.66	4.06		4.31	

* Missing Value

Groundwater Discharge Rates Estimated by the Computer Program by Pettyjohn and Henning (1979)

RIVER	YEAR	PRECIPITATION (in.)	TOTAL DISCHARGE Local Minima	TOTAL DISCHARGE Sliding Interval	TOTAL DISCHARGE Interval Days	GW DISCHARGE Local Minima	GW DISCHARGE Sliding Interval	% OF GW/TOTAL Local Minima	% OF GW/TOTAL Sliding Interval
Black near Fargo	1961	29.49	2.49	2.49	7	1.26	1.35	50.44	53.99
	1985	38.88	19.94	19.94	7	6.47	8.26	32.47	41.43
	1986	36.90	14.16	14.16	7	3.44	6.72	24.31	47.45
	1987	27.70	9.61	9.61	7	4.17	5.17	43.33	53.73
	1988	22.16	6.27	6.27	7	2.74	3.04	43.68	48.48
	1989	27.09	4.08	4.08	7	1.83	2.08	44.80	50.90
	Mean	30.37	9.43	9.43		3.32	4.44	39.84	49.33
Cass at Frankenmuth	1961	27.27	4.06	4.06	7	2.53	2.66	62.27	65.47
	1985	36.26	16.25	16.25	7	7.51	8.99	46.23	55.38
	1986	41.81	13.53	13.53	7	8.35	7.87	61.72	58.15
	1987	28.05	9.59	9.59	7	6.15	6.09	64.16	63.50
	1988	29.53	7.23	7.23	7	4.25	4.47	58.89	61.84
	1989	28.89	7.15	7.15	7	4.04	4.36	56.45	60.92
	Mean	31.97	9.64	9.22		5.47	5.74	58.29	60.88
Flint near Fosters	1961	30.54	5.08	5.08	9	3.16	3.22	62.13	63.44
	1985	40.62	17.85	17.85	7	8.52	11.05	47.73	61.91
	1986	37.54	15.78	15.78	7	8.46	11.19	53.65	70.92
	1987	29.24	11.09	11.09	7	7.63	8.78	68.79	79.11
	1988	27.64	9.23	9.23	7	5.48	6.72	59.35	72.87
	1989	32.34	8.46	8.46	7	5.85	6.13	69.13	72.48
	Mean	32.99	11.25	11.25		6.52	7.85	60.13	70.12

RIVER	YEAR	PRECIPITATION (in.)	TOTAL DISCHARGE Local Minima	Sliding Interval	Interval Days	GW DISCHARGE Local Minima	Sliding Interval	% OF GW/TOTAL Local Minima	Sliding Interval
Pigeon near Owendale	1958	22.24	5.94	5.94	5	3.08	3.97	51.88	66.76
	1961	27.22	2.96	2.96	5	1.92	2.02	65.03	68.21
	1962	25.74	4.56	4.56	5	2.15	2.79	47.16	61.21
	1963	23.78	4.07	4.07	5	2.42	2.50	59.45	61.42
	1964	22.70	1.39	1.39	5	0.96	1.01	68.95	72.36
	1973	31.66	14.78	14.78	5	7.36	8.41	49.79	56.92
	1977	30.48	4.55	4.55	5	2.35	2.52	51.67	55.41
	1976	35.35	15.53	15.53	5	7.61	8.29	48.98	53.40
	1978	24.53	10.49	10.49	5	5.67	6.21	54.05	59.15
	1979	29.27	8.62	8.62	5	4.34	4.99	50.33	57.98
	Mean	27.30	7.29	7.29		3.79	4.27	54.73	61.28
Shiawassee at Owosso	1961	27.50	5.02	5.02	7	3.89	3.99	77.68	79.69
	1985	41.16	12.90	12.90	7	7.89	9.16	61.19	70.97
	1986	41.89	12.26	12.26	7	7.02	9.15	57.19	74.57
	1987	32.93	8.64	8.64	7	5.77	7.31	66.76	84.56
	1988	*	8.03	8.03	7	5.21	6.19	64.87	77.14
	1989	31.53	11.29	11.29	7	8.49	8.84	75.13	78.27
	Mean	35.00	9.69	9.69		6.38	7.44	67.14	77.53
Tittabawassee at Midland	1961	31.60	6.27	6.27	9	3.64	3.82	58.03	60.95
	1985	35.53	11.76	11.76	9	5.33	5.63	45.34	47.85
	1986	39.52	12.93	12.93	9	6.54	6.86	50.55	53.07
	1987	27.08	7.84	7.84	9	4.71	4.91	60.06	62.68
	1988	31.80	8.15	8.15	9	4.14	4.39	50.84	53.94
	1989	24.45	9.43	9.43	9	4.42	4.99	46.90	52.99
	Mean	31.66	9.39	9.39		4.79	5.10	51.95	55.25

APPENDIX B

Appendix B

LINEAR PROGRAMMING MODEL FOR CASS RIVER WATERSHED CROP MIX (Crop Gross Margin over Variable Cost, Irrigation Water Demand and Streamflow all at 75% Exceedence Level)

Objective Function: Maximize Crop Gross Margin over Variable Cost

MAX -32.02 CORN40NO + 90.70 CORN40IR + 5.95 CORN41NO + 195.22 CORN41IR + 20.05 CORN42NO + 246.40 CORN42IR +255.51 CORN43NO + 249.95 CORN43IR - 8.40 CORN46NO + 232.17 CORN46IR + 44.69 CORN48NO + 274.34 CORN48IR -49.55 CORN51NO + 235.22 CORN51IR + 7.60 CORN64NO + 250.72 CORN64IR + 63.74 CORN69NO + 274.08 CORN69IR + 52.43 CORN70NO + 275.48 CORN70IR + 57.89 CORN73NO + 243.35 CORN73IR + 16.75 CORN74NO + 128.03 CORN74IR - 67.42 SOYB40NO + 53.94 SOYB40IR - 34.20 SOYB41NO + 125.52 SOYB41IR - 34.81 SOYB42NO +108.30 SOYB42IR + 144.58 SOYB43NO + 141.52 SOYB43IR - 34.81 SOYB46NO + 75.08 SOYB46IR - 33.00 SOYB48NO + 114.34 SOYB48IR - 61.99 SOYB51NO + 124.61 SOYB51IR - 52.32 SOYB64NO + 58.17 SOYB64IR - 33.60 SOYB69NO + 105.28 SOYB69IR - 33.60 SOYB70NO + 107.40 SOYB70IR - 26.35 SOYB73NO + 146.96 SOYB73IR - 45.68 SOYB74NO + 105.28 SOYB74IR - 8.11 DRYB40NO + 675.17 DRYB40IR + 130.20 DRYB41NO + 680.65 DRYB41IR + 146.35 DRYB42NO + 641.29 DRYB42IR + 659.15 DRYB43NO + 641.49 DRYB43IR + 113.07 DRYB46NO + 639.50 DRYB46IR + 175.85 DRYB48NO + 593.46 DRYB48IR + 14.81 DRYB51NO + 658.63 DRYB51IR + 81.58 DRYB64NO + 629.53 DRYB64IR + 140.37 DRYB69NO +590.07 DRYB69IR + 154.92 DRYB70NO + 606.32 DRYB70IR +157.91 DRYB73NO + 607.41 DRYB73IR + 118.65 DRYB74NO + 700.09 DRYB74IR + 351.82 SUGBTNO + 418.45 SUGBTIR

Resources Constraints:

1. Total Agricultural Land Acreage Limit

CORN40NO + CORN40IR + CORN41NO + CORN41IR + CORN42NO + CORN42IR + CORN43NO + CORN43IR + CORN46NO + CORN46IR + CORN48NO + CORN48IR + CORN51NO + CORN51IR + CORN64NO + CORN64IR + CORN69NO + CORN69IR + CORN70NO + CORN70IR + CORN73NO + CORN73IR + CORN74NO + CORN74IR + SOYB40NO + SOYB40IR + SOYB41NO + SOYB41IR + SOYB42NO + SOYB42IR + SOYB43NO + SOYB43IR + SOYB46NO + SOYB46IR + SOYB48NO + SOYB48IR + SOYB51NO + SOYB51IR + SOYB64NO + SOYB64IR + SOYB69NO + SOYB69IR + SOYB70NO + SOYB70IR + SOYB73NO + SOYB73IR + SOYB74NO + SOYB74IR + DRYB40NO + DRYB40IR + DRYB41NO + DRYB41IR + DRYB42NO + DRYB42IR + DRYB43NO + DRYB43IR + DRYB46NO + DRYB46IR + DRYB48NO + DRYB48IR + DRYB51NO + DRYB51IR + DRYB64NO + DRYB64IR + DRYB69NO + DRYB69IR + DRYB70NO + DRYB70IR + DRYB73NO + DRYB73IR + DRYB74NO + DRYB74IR + SUGBTNO + SUGBTIR = 392713

2. July 75% Exceedence Streamflow Limit

129 CORN40IR + 107 CORN41IR + 105 CORN42IR + 95 CORN43IR +
106 CORN46IR + 110 CORN48IR + 105 CORN51IR + 98 CORN64IR +
110 CORN69IR + 109 CORN70IR + 117 CORN73IR + 109 CORN74IR +
129 SOYB40IR + 160 SOYB41IR + 151 SOYB42IR + 97 SOYB43IR +
142 SOYB46IR + 118 SOYB48IR + 141 SOYB51IR + 142 SOYB64IR +
159 SOYB69IR + 140 SOYB70IR + 155 SOYB73IR + 154 SOYB74IR +
130 DRYB40IR + 154 DRYB41IR + 138 DRYB42IR + 94 DRYB43IR +
143 DRYB46IR + 116 DRYB48IR + 141 DRYB51IR +145 DRYB64IR +
114 DRYB69IR + 135 DRYB70IR + 120 DRYB73IR + 142 DRYB74IR +
61 SUGBTIR = 543489

3. Sugarbeet Acreage Limit due to processing capacity

SUGBTNO + SUGBTIR <= 39271

4. Agricultural Land Limit on Soil Association 40

CORN40NO + CORN40IR + SOYB40NO + SOYB40IR + DRYB40NO +
DRYB40IR < 22366

5. Agricultural Land Limit on Soil Association 41

CORN41NO + CORN41IR + SOYB41NO + SOYB41IR + DRYB41NO +
DRYB41IR < 84910

6. Agricultural Land Limit on Soil Association 42

CORN42NO + CORN42IR + SOYB42NO + SOYB42IR + DRYB42NO +
DRYB42IR < 84161

7. Agricultural Land Limit on Soil Association 43

CORN43NO + CORN43IR + SOYB43NO + SOYB43IR + DRYB43NO +
DRYB43IR < 20713

8. Agricultural Land Limit on Soil Association 46

CORN46NO + CORN46IR + SOYB46NO + SOYB46IR + DRYB46NO +
DRYB46IR < 24506

9. Agricultural Land Limit on Soil Association 48

CORN48NO + CORN48IR + SOYB48NO + SOYB48IR + DRYB48NO +
DRYB48IR < 4034

10. Agricultural Land Limit on Soil Association 51

CORN51NO + CORN51IR + SOYB51NO + SOYB51IR + DRYB51NO +
DRYB51IR < 43819

11. Agricultural Land Limit on Soil Association 64

CORN64NO + CORN64IR + SOYB64NO + SOYB64IR + DRYB64NO + DRYB64IR < 57902

12. Agricultural Land Limit on Soil Association 69

CORN69NO + CORN69IR + SOYB69NO + SOYB69IR + DRYB69NO + DRYB69IR < 16191

13. Agricultural Land Limit on Soil Association 70

CORN70NO + CORN70IR + SOYB70NO + SOYB70IR + DRYB70NO + DRYB70IR < 16274

14. Agricultural Land on Soil Association 73

CORN73NO + CORN73IR + SOYB73NO + SOYB73IR + DRYB73NO + DRYB73IR < 14939

15. Agricultural Land on Soil Association 74

CORN74NO + CORN74IR + SOYB74NO + SOYB74IR + DRYB74NO + DRYB74IR < 2898

16. Current Dry Bean Acreage Limit

DRYB40NO + DRYB40IR + DRYB41NO + DRYB41IR + DRYB42NO + DRYB42IR + DRYB43NO + DRYB43IR + DRYB46NO + DRYB46IR + DRYB48NO + DRYB48IR + DRYB51NO + DRYB51IR + DRYB64NO + DRYB64IR + DRYB69NO + DRYB69IR + DRYB70NO + DRYB70IR + DRYB73NO + DRYB73IR + DRYB74NO + DRYB74IR < 66761

END

Variable explanation:

CORN40NO -Acreage of non-irrigated corn in soil association 40
CORN40IR -Acreage of irrigated corn in soil association 40
SOYB40NO -Acreage of non-irrigated soybeans in soil association 40
SOYB40IR -Acreage of irrigated soybeans in soil association 40
DRYB40NO -Acreage of non-irrigated dry beans in soil association 40
DRYB40IR -Acreage of irrigated dry beans in soil association 40
SUGBTNO -Acreage of non-irrigated sugarbeets in all soils
SUGBTIR -Acreage of irrigated sugarbeets in all soils

APPENDIX C

Appendix C

Linear Programming Model Output for Cass River Watershed Crop Mix (Crop Gross Margin over Variable Cost, Irrigation Water Demand, and July Streamflow all at 75% Probability Level)

```
MAX   - 32.01999 CORN40NO + 90.7 CORN40IR + 5.95 CORN41NO
      + 195.21999 CORN41IR + 20.04999 CORN42NO
      + 246.39999 CORN42IR + 255.50999 CORN43NO + 249.95
        CORN43IR - 8.4 CORN46NO + 232.17 CORN46IR + 44.68999
        CORN48NO + 274.33984 CORN48IR - 49.54999 CORN51NO
      + 235.21999 CORN51IR + 7.6 CORN64NO + 250.71999 CORN64IR
      + 63.73999 CORN69NO + 274.07983 CORN69IR + 52.42999
        CORN70NO + 275.47998 CORN70IR + 57.89 CORN73NO +
        243.34999 CORN73IR + 16.75 CORN74NO + 128.03 CORN74IR
      - 67.42 SOYB40NO + 53.93999 SOYB40IR - 34.2 SOYB41NO +
        125.51999 SOYB41IR - 34.81 SOYB42NO + 108.29999
        SOYB42IR + 144.57999 SOYB43NO + 141.51999 SOYB43IR -
        34.81 SOYB46NO + 75.07999 SOYB46IR - 33 SOYB48NO +
        114.34 SOYB48IR - 61.98999 SOYB51NO + 124.60999
        SOYB51IR - 52.31999 SOYB64NO + 58.17 SOYB64IR
      - 33.59999 SOYB69NO + 105.28 SOYB69IR - 33.59999
        SOYB70NO + 107.39999 SOYB70IR - 26.34999 SOYB73NO
      + 146.95999 SOYB73IR - 45.67999 SOYB74NO + 105.28
        SOYB74IR - 8.11 DRYB40NO + 675.16992 DRYB40IR + 130.2
        DRYB41NO + 680.6499 DRYB41IR + 146.34999 DRYB42NO
      + 641.28979 DRYB42IR + 659.1499 DRYB43NO + 641.48999
        DRYB43IR + 113.06999 DRYB46NO + 639.5 DRYB46IR +
        175.84999 DRYB48NO + 593.45996 DRYB48IR + 14.81
        DRYB51NO + 658.62988 DRYB51IR + 81.57999 DRYB64NO
      + 629.52979 DRYB64IR + 140.37 DRYB69NO + 590.06982
        DRYB69IR + 154.92 DRYB70NO + 606.31982 DRYB70IR +
        157.90999 DRYB73NO + 607.40991 DRYB73IR + 118.64999
        DRYB74NO + 700.08984 DRYB74IR + 351.81982 SUGBTNO +
        418.44995 SUGBTIR

SUBJECT TO

      2) CORN40NO + CORN40IR + CORN41NO + CORN41IR + CORN42NO
      + CORN42IR + CORN43NO + CORN43IR + CORN46NO + CORN46IR
      + CORN48NO + CORN48IR + CORN51NO + CORN51IR + CORN64NO
      + CORN64IR + CORN69NO + CORN69IR + CORN70NO + CORN70IR
      + CORN73NO + CORN73IR + CORN74NO + CORN74IR + SOYB40NO
      + SOYB40IR + SOYB41NO + SOYB41IR + SOYB42NO + SOYB42IR
      + SOYB43NO + SOYB43IR + SOYB46NO + SOYB46IR + SOYB48NO
      + SOYB48IR + SOYB51NO + SOYB51IR + SOYB64NO + SOYB64IR
      + SOYB69NO + SOYB69IR + SOYB70NO + SOYB70IR + SOYB73NO
      + SOYB73IR + SOYB74NO + SOYB74IR + DRYB40NO + DRYB40IR
      + DRYB41NO + DRYB41IR + DRYB42NO + DRYB42IR + DRYB43NO
      + DRYB43IR + DRYB46NO + DRYB46IR + DRYB48NO + DRYB48IR
      + DRYB51NO + DRYB51IR + DRYB64NO + DRYB64IR + DRYB69NO
      + DRYB69IR + DRYB70NO + DRYB70IR + DRYB73NO + DRYB73IR
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+ DRYB74NO + DRYB74IR + SUGBTNO + SUGBTIR = 392713

3) 129 CORN40IR + 107 CORN41IR + 105 CORN42IR
+ 95 CORN43IR + 106 CORN46IR + 110 CORN48IR + 105
CORN51IR + 98 CORN64IR + 110 CORN69IR + 109 CORN70IR
+ 117 CORN73IR + 109 CORN74IR + 129 SOYB40IR + 160
SOYB41IR + 151 SOYB42IR + 97 SOYB43IR + 142 SOYB46IR
+ 118 SOYB48IR + 141 SOYB51IR + 142 SOYB64IR + 159
SOYB69IR + 140 SOYB70IR + 155 SOYB73IR + 154 SOYB74IR
+ 130 DRYB40IR + 154 DRYB41IR + 138 DRYB42IR
+ 94 DRYB43IR + 143 DRYB46IR + 116 DRYB48IR + 141
DRYB51IR + 145 DRYB64IR + 114 DRYB69IR + 135 DRYB70IR
+ 120 DRYB73IR + 142 DRYB74IR + 61 SUGBTIR = 543489

4) SUGBTNO + SUGBTIR <= 39271

5) CORN40NO + CORN40IR + SOYB40NO + SOYB40IR +
DRYB40NO + DRYB40IR <= 22366

6) CORN41NO + CORN41IR + SOYB41NO + SOYB41IR + DRYB41NO
+ DRYB41IR <= 84910

7) CORN42NO + CORN42IR + SOYB42NO + SOYB42IR + DRYB42NO
+ DRYB42IR <= 84161

8) CORN43NO + CORN43IR + SOYB43NO + SOYB43IR +
DRYB43NO + DRYB43IR <= 20713

9) CORN46NO + CORN46IR + SOYB46NO + SOYB46IR + DRYB46NO
+ DRYB46IR <= 24506

10) CORN48NO + CORN48IR + SOYB48NO + SOYB48IR + DRYB48NO
+ DRYB48IR <= 4034

11) CORN51NO + CORN51IR + SOYB51NO + SOYB51IR + DRYB51NO
+ DRYB51IR <= 43819

12) CORN64NO + CORN64IR + SOYB64NO + SOYB64IR + DRYB64NO
+ DRYB64IR <= 57902

13) CORN69NO + CORN69IR + SOYB69NO + SOYB69IR + DRYB69NO
+ DRYB69IR <= 16191

14) CORN70NO + CORN70IR + SOYB70NO + SOYB70IR + DRYB70NO
+ DRYB70IR <= 16274

15) CORN73NO + CORN73IR + SOYB73NO + SOYB73IR + DRYB73NO
+ DRYB73IR <= 14939

16) CORN74NO + CORN74IR + SOYB74NO + SOYB74IR + DRYB74NO
+ DRYB74IR <= 2898

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    17) DRYB40NO + DRYB40IR + DRYB41NO + DRYB41IR + DRYB42NO
     + DRYB42IR + DRYB43NO + DRYB43IR + DRYB46NO + DRYB46IR
     + DRYB48NO + DRYB48IR + DRYB51NO + DRYB51IR + DRYB64NO
     + DRYB64IR + DRYB69NO + DRYB69IR + DRYB70NO + DRYB70IR
     + DRYB73NO + DRYB73IR + DRYB74NO + DRYB74IR <=   66761
END

LP OPTIMUM FOUND AT STEP     23

       OBJECTIVE FUNCTION VALUE

       1)     40197504.0
```

VARIABLE	VALUE	REDUCED COST
CORN40NO	18185.312500	0.000000
CORN40IR	0.000000	453.700928
CORN41NO	84910.000000	0.000000
CORN41IR	0.000000	288.846680
CORN42NO	46327.683600	0.000000
CORN42IR	0.000000	242.829956
CORN43NO	0.000000	277.339844
CORN43IR	0.000000	707.395996
CORN46NO	24506.000000	0.000000
CORN46IR	0.000000	233.078445
CORN48NO	0.000000	4.860001
CORN48IR	0.000000	266.732178
CORN51NO	4547.996090	0.000000
CORN51IR	0.000000	184.410156
CORN64NO	57902.000000	0.000000
CORN64IR	0.000000	194.781570
CORN69NO	16191.000000	0.000000
CORN69IR	0.000000	281.182129
CORN70NO	16274.000000	0.000000
CORN70IR	0.000000	264.003662
CORN73NO	14939.000000	0.000000
CORN73IR	0.000000	337.340576
CORN74NO	2898.000000	0.000000
CORN74IR	0.000000	375.773193
SOYB40NO	0.000000	35.400009
SOYB40IR	0.000000	490.460937
SOYB41NO	0.000000	40.149994
SOYB41IR	0.000000	595.370605
SOYB42NO	0.000000	54.859985
SOYB42IR	0.000000	586.475342
SOYB43NO	0.000000	388.269531
SOYB43IR	0.000000	824.762451
SOYB46NO	0.000000	26.409988
SOYB46IR	0.000000	551.029785
SOYB48NO	0.000000	82.549988
SOYB48IR	0.000000	462.478760
SOYB51NO	0.000000	12.440002

SOYB51IR	0.000000	455.881592
SOYB64NO	0.000000	59.919983
SOYB64IR	0.000000	583.939697
SOYB69NO	0.000000	97.339981
SOYB69IR	0.000000	668.932373
SOYB70NO	0.000000	86.029984
SOYB70IR	0.000000	570.603027
SOYB73NO	0.000000	84.239990
SOYB73IR	0.000000	603.529053
SOYB74NO	0.000000	62.429993
SOYB74IR	0.000000	599.600342
DRYB40NO	0.000000	102.390015
DRYB40IR	4180.683590	0.000000
DRYB41NO	0.000000	2.050003
DRYB41IR	0.000000	139.730896
DRYB42NO	37833.312500	0.000000
DRYB42IR	0.000000	121.696854
DRYB43NO	20713.000000	0.000000
DRYB43IR	0.000000	437.687500
DRYB46NO	0.000000	4.830002
DRYB46IR	0.000000	117.378693
DRYB48NO	4034.000000	0.000000
DRYB48IR	0.000000	100.722488
DRYB51NO	0.000000	61.940018
DRYB51IR	0.000000	48.162064
DRYB64NO	0.000000	52.320007
DRYB64IR	0.000000	152.285675
DRYB69NO	0.000000	49.669998
DRYB69IR	0.000000	109.365860
DRYB70NO	0.000000	23.809998
DRYB70IR	0.000000	175.641800
DRYB73NO	0.000000	26.280014
DRYB73IR	0.000000	112.986084
DRYB74NO	0.000000	24.400009
DRYB74IR	0.000000	77.470352
SUGBTNO	39271.000000	0.000000
SUGBTIR	0.000000	205.941162

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	-49.549988
3)	0.000000	4.468382
4)	0.000000	401.369629
5)	0.000000	17.529999
6)	0.000000	55.499985
7)	0.000000	69.599976
8)	0.000000	582.399658
9)	0.000000	41.149979
10)	0.000000	99.099976
11)	39271.000000	0.000000
12)	0.000000	57.149979
13)	0.000000	113.289978
14)	0.000000	101.979980

15)	0.000000	107.439987
16)	0.000000	66.299988
17)	0.000000	126.300003

NO. ITERATIONS= 23

RANGES IN WHICH THE BASIS IS UNCHANGED:

		OBJ COEFFICIENT RANGES	
VARIABLE	CURRENT COEF	ALLOWABLE INCREASE	ALLOWABLE DECREASE
CORN40NO	-32.019989	44.404755	17.529999
CORN40IR	90.699997	453.700928	INFINITY
CORN41NO	5.950000	INFINITY	2.050003
CORN41IR	195.219986	288.846680	INFINITY
CORN42NO	20.049988	2.050003	4.860001
CORN42IR	246.399994	242.829956	INFINITY
CORN43NO	255.509995	277.339844	INFINITY
CORN43IR	249.949997	707.395996	INFINITY
CORN46NO	-8.400000	INFINITY	4.830002
CORN46IR	232.169998	233.078445	INFINITY
CORN48NO	44.689987	4.860001	INFINITY
CORN48IR	274.339844	266.732178	INFINITY
CORN51NO	-49.549988	17.529999	12.440002
CORN51IR	235.219986	184.410156	INFINITY
CORN64NO	7.599999	INFINITY	52.320007
CORN64IR	250.719986	194.781570	INFINITY
CORN69NO	63.739990	INFINITY	49.669998
CORN69IR	274.079834	281.182129	INFINITY
CORN70NO	52.429993	INFINITY	23.809998
CORN70IR	275.479980	264.003662	INFINITY
CORN73NO	57.889999	INFINITY	26.280014
CORN73IR	243.349991	337.340576	INFINITY
CORN74NO	16.750000	INFINITY	24.400009
CORN74IR	128.029999	375.773193	INFINITY
SOYB40NO	-67.419998	35.400009	INFINITY
SOYB40IR	53.939987	490.460937	INFINITY
SOYB41NO	-34.199997	40.149994	INFINITY
SOYB41IR	125.519989	595.370605	INFINITY
SOYB42NO	-34.809998	54.859985	INFINITY
SOYB42IR	108.299988	586.475342	INFINITY
SOYB43NO	144.579987	388.269531	INFINITY
SOYB43IR	141.519989	824.762451	INFINITY
SOYB46NO	-34.809998	26.409988	INFINITY
SOYB46IR	75.079987	551.029785	INFINITY
SOYB48NO	-33.000000	82.549988	INFINITY
SOYB48IR	114.339996	462.478760	INFINITY
SOYB51NO	-61.989990	12.440002	INFINITY
SOYB51IR	124.609985	455.881592	INFINITY
SOYB64NO	-52.319992	59.919983	INFINITY

SOYB64IR	58.169998	583.939697	INFINITY
SOYB69NO	-33.599991	97.339981	INFINITY
SOYB69IR	105.279999	668.932373	INFINITY
SOYB70NO	-33.599991	86.029984	INFINITY
SOYB70IR	107.399994	570.603027	INFINITY
SOYB73NO	-26.349991	84.239990	INFINITY
SOYB73IR	146.959991	603.529053	INFINITY
SOYB74NO	-45.679993	62.429993	INFINITY
SOYB74IR	105.279999	599.600342	INFINITY
DRYB40NO	-8.110000	102.390015	INFINITY
DRYB40IR	675.169922	INFINITY	44.404755
DRYB41NO	130.199997	2.050003	INFINITY
DRYB41IR	680.649902	139.730896	INFINITY
DRYB42NO	146.349991	4.860001	2.050003
DRYB42IR	641.289795	121.696854	INFINITY
DRYB43NO	659.149902	INFINITY	277.339844
DRYB43IR	641.489990	437.687500	INFINITY
DRYB46NO	113.069992	4.830002	INFINITY
DRYB46IR	639.500000	117.378693	INFINITY
DRYB48NO	175.849991	INFINITY	4.860001
DRYB48IR	593.459961	100.722488	INFINITY
DRYB51NO	14.809999	61.940018	INFINITY
DRYB51IR	658.629883	48.162064	INFINITY
DRYB64NO	81.579987	52.320007	INFINITY
DRYB64IR	629.529785	152.285675	INFINITY
DRYB69NO	140.369995	49.669998	INFINITY
DRYB69IR	590.069824	109.365860	INFINITY
DRYB70NO	154.919998	23.809998	INFINITY
DRYB70IR	606.319824	175.641800	INFINITY
DRYB73NO	157.909988	26.280014	INFINITY
DRYB73IR	607.409912	112.986084	INFINITY
DRYB74NO	118.649994	24.400009	INFINITY
DRYB74IR	700.089844	77.470352	INFINITY
SUGBTNO	351.819824	INFINITY	205.941162
SUGBTIR	418.449951	205.941162	INFINITY

RIGHTHAND SIDE RANGES

ROW	CURRENT RHS	ALLOWABLE INCREASE	ALLOWABLE DECREASE
2	392713.000000	39271.000000	4547.996090
3	543489.000000	2364090.000000	543488.875000
4	39271.000000	4547.996090	39271.000000
5	22366.000000	4547.996090	18185.312500
6	84910.000000	4547.996090	39271.000000
7	84161.000000	4547.996090	39271.000000
8	20713.000000	4547.996090	20713.000000
9	24506.000000	4547.996090	24506.000000
10	4034.000000	4547.996090	4034.000000
11	43819.000000	INFINITY	39271.000000
12	57902.000000	4547.996090	39271.000000
13	16191.000000	4547.996090	16191.000000
14	16274.000000	4547.996090	16274.000000

15	14939.000000	4547.996090	14939.000000
16	2898.000000	4547.996090	2898.000000
17	66761.000000	46327.683600	37833.312500

APPENDIX D

Appendix D

Linear Programming Model Output for Cass River Watershed Crop Mix (Crop Gross Margin over Variable Cost and Irrigation Water Demand at Mean Level, and Streamflow at 50% Exceedence Level)

```
 MAX     149.71999 CORN40NO + 332.81982 CORN40IR
       + 216.07999 CORN41NO + 395.86987 CORN41IR
       + 294.75977 CORN42NO + 392.85986 CORN42IR
       + 436.95996 CORN43NO + 427.30981 CORN43IR + 141.5
         CORN46NO + 382.11987 CORN46IR + 272.32983 CORN48NO
       + 439.62988 CORN48IR + 98.84 CORN51NO + 390.96997
         CORN51IR + 208.81 CORN64NO + 394.43994 CORN64IR +
         262.20996 CORN69NO + 434.56982 CORN69IR + 253.2
         CORN70NO + 432.98999 CORN70IR + 249.56999 CORN73NO +
         399.17993 CORN73IR + 229.98 CORN74NO + 381.16992
         CORN74IR + 9.3 SOYB40NO + 173.39999 SOYB40IR
       + 56.7 SOYB41NO + 249.92999 SOYB41IR + 59.79999 SOYB42NO
       + 221.56999 SOYB42IR + 264.1499 SOYB43NO + 257.30981
         SOYB43IR + 44.25999 SOYB46NO + 204.48 SOYB46IR
       + 80 SOYB48NO + 251.87 SOYB48IR + 2.3 SOYB51NO
       + 250.31999 SOYB51IR + 37.26999 SOYB64NO + 178.84
         SOYB64IR + 71.45999 SOYB69NO + 245.65999 SOYB69IR +
         62.51999 SOYB70NO + 236.34 SOYB70IR + 79.23 SOYB73NO
       + 268.96997 SOYB73IR  + 45.03999 SOYB74NO + 227.78999
         SOYB74IR + 231.21999 DRYB40NO + 985.6499 DRYB40IR
       + 427.58984 DRYB41NO + 970.69995 DRYB41IR + 438.69995
         DRYB42NO + 937.97998 DRYB42IR + 930.96997 DRYB43NO +
         942.42993 DRYB43IR + 373 DRYB46NO + 917.96997 DRYB46IR
       + 423.13989 DRYB48NO + 878.94995 DRYB48IR + 218.62999
         DRYB51NO + 927.10986 DRYB51IR + 378.92993 DRYB64NO
       + 923.40991 DRYB64IR + 380.65991 DRYB69NO
       + 867.82983 DRYB69IR + 389.5498 DRYB70NO
       + 892.27979 DRYB70IR + 405.10986 DRYB73NO
       + 881.41992 DRYB73IR + 438.69995 DRYB74NO
       + 1004.91992 DRYB74IR + 680.86987 SUGBTNO
       + 753.08984 SUGBTIR

 SUBJECT TO

       2) CORN40NO + CORN40IR + CORN41NO + CORN41IR +
          CORN42NO + CORN42IR + CORN43NO + CORN43IR + CORN46NO
        + CORN46IR + CORN48NO + CORN48IR + CORN51NO + CORN51IR
        + CORN64NO + CORN64IR + CORN69NO + CORN69IR + CORN70NO
        + CORN70IR + CORN73NO + CORN73IR + CORN74NO + CORN74IR
        + SOYB40NO + SOYB40IR + SOYB41NO + SOYB41IR + SOYB42NO
        + SOYB42IR + SOYB43NO + SOYB43IR + SOYB46NO + SOYB46IR
        + SOYB48NO + SOYB48IR + SOYB51NO + SOYB51IR + SOYB64NO
        + SOYB64IR + SOYB69NO + SOYB69IR + SOYB70NO + SOYB70IR
        + SOYB73NO + SOYB73IR + SOYB74NO + SOYB74IR + DRYB40NO
        + DRYB40IR + DRYB41NO + DRYB41IR + DRYB42NO + DRYB42IR
        + DRYB43NO + DRYB43IR + DRYB46NO + DRYB46IR + DRYB48NO
```

+ DRYB48IR + DRYB51NO + DRYB51IR + DRYB64NO + DRYB64IR
+ DRYB69NO + DRYB69IR + DRYB70NO + DRYB70IR + DRYB73NO
+ DRYB73IR + DRYB74NO + DRYB74IR + SUGBTNO + SUGBTIR =
392713

3) 96 CORN40IR + 82 CORN41IR + 69 CORN42IR + 37 CORN43IR
+ 84 CORN46IR + 70 CORN48IR + 79 CORN51IR + 74 CORN64IR
+ 83 CORN69IR + 81 CORN70IR + 75 CORN73IR + 85 CORN74IR
+ 92 SOYB40IR + 123 SOYB41IR + 94 SOYB42IR + 60 SOYB43IR
+ 101 SOYB46IR + 107 SOYB48IR + 115 SOYB51IR + 91
SOYB64IR + 120 SOYB69IR + 113 SOYB70IR + 116 SOYB73IR
+ 109 SOYB74IR + 105 DRYB40IR + 110 DRYB41IR + 95
DRYB42IR + 51 DRYB43IR + 103 DRYB46IR + 104 DRYB48IR
+ 115 DRYB51IR + 99 DRYB64IR + 108 DRYB69IR + 110
DRYB70IR + 113 DRYB73IR + 105 DRYB74IR + 94 SUGBTIR =
1135704

4) SUGBTNO + SUGBTIR <= 39271

5) CORN40NO + CORN40IR + SOYB40NO + SOYB40IR +
DRYB40NO + DRYB40IR <= 22366

6) CORN41NO + CORN41IR + SOYB41NO + SOYB41IR + DRYB41NO
+ DRYB41IR <= 84910

7) CORN42NO + CORN42IR + SOYB42NO + SOYB42IR + DRYB42NO
+ DRYB42IR <= 84161

8) CORN43NO + CORN43IR + SOYB43NO + SOYB43IR + DRYB43NO
+ DRYB43IR <= 20713

9) CORN46NO + CORN46IR + SOYB46NO + SOYB46IR + DRYB46NO
+ DRYB46IR <= 24506

10) CORN48NO + CORN48IR + SOYB48NO + SOYB48IR + DRYB48NO
+ DRYB48IR <= 4034

11) CORN51NO + CORN51IR + SOYB51NO + SOYB51IR + DRYB51NO
+ DRYB51IR <= 43819

12) CORN64NO + CORN64IR + SOYB64NO + SOYB64IR + DRYB64NO
+ DRYB64IR <= 57902

13) CORN69NO + CORN69IR + SOYB69NO + SOYB69IR + DRYB69NO
+ DRYB69IR <= 16191

14) CORN70NO + CORN70IR + SOYB70NO + SOYB70IR + DRYB70NO
+ DRYB70IR <= 16274

15) CORN73NO + CORN73IR + SOYB73NO + SOYB73IR + DRYB73NO
+ DRYB73IR <= 14939

16) CORN74NO + CORN74IR + SOYB74NO + SOYB74IR + DRYB74NO
+ DRYB74IR <= 2898

17) DRYB40NO + DRYB40IR + DRYB41NO + DRYB41IR + DRYB42NO
+ DRYB42IR + DRYB43NO + DRYB43IR + DRYB46NO + DRYB46IR
+ DRYB48NO + DRYB48IR + DRYB51NO + DRYB51IR + DRYB64NO
+ DRYB64IR + DRYB69NO + DRYB69IR + DRYB70NO + DRYB70IR
+ DRYB73NO + DRYB73IR + DRYB74NO + DRYB74IR <= 66761

END

LP OPTIMUM FOUND AT STEP 31

OBJECTIVE FUNCTION VALUE

1) 139375280.

VARIABLE	VALUE	REDUCED COST
CORN40NO	11549.769500	0.000000
CORN40IR	0.000000	387.797852
CORN41NO	74184.187500	0.000000
CORN41IR	0.000000	307.852295
CORN42NO	84161.000000	0.000000
CORN42IR	0.000000	312.232910
CORN43NO	0.000000	282.500244
CORN43IR	0.000000	512.183838
CORN46NO	0.000000	19.990143
CORN46IR	0.000000	278.906006
CORN48NO	4034.000000	0.000000
CORN48IR	0.000000	248.979828
CORN51NO	4547.996090	0.000000
CORN51IR	0.000000	177.671631
CORN64NO	57902.000000	0.000000
CORN64IR	0.000000	254.437286
CORN69NO	16191.000000	0.000000
CORN69IR	0.000000	321.229004
CORN70NO	16274.000000	0.000000
CORN70IR	0.000000	301.905029
CORN73NO	14939.000000	0.000000
CORN73IR	0.000000	296.404297
CORN74NO	2898.000000	0.000000
CORN74IR	0.000000	354.292725
SOYB40NO	0.000000	140.419983
SOYB40IR	0.000000	523.430420
SOYB41NO	0.000000	159.379990
SOYB41IR	0.000000	697.613037
SOYB42NO	0.000000	234.959778
SOYB42IR	0.000000	632.193848
SOYB43NO	0.000000	455.310059
SOYB43IR	0.000000	818.961426
SOYB46NO	0.000000	117.230148
SOYB46IR	0.000000	557.642334

SOYB48NO	0.000000	192.329834
SOYB48IR	0.000000	656.773193
SOYB51NO	0.000000	96.539993
SOYB51IR	0.000000	532.407959
SOYB64NO	0.000000	171.540009
SOYB64IR	0.000000	571.133789
SOYB69NO	0.000000	190.749969
SOYB69IR	0.000000	730.172363
SOYB70NO	0.000000	190.680008
SOYB70IR	0.000000	688.854492
SOYB73NO	0.000000	170.339996
SOYB73IR	0.000000	670.435059
SOYB74NO	0.000000	184.940002
SOYB74IR	0.000000	650.396729
DRYB40NO	0.000000	130.009766
DRYB40IR	10816.226600	0.000000
DRYB41NO	10725.769500	0.000000
DRYB41IR	0.000000	111.043945
DRYB42NO	0.000000	67.569672
DRYB42IR	0.000000	133.240814
DRYB43NO	20713.000000	0.000000
DRYB43IR	0.000000	291.829590
DRYB46NO	24506.000000	0.000000
DRYB46IR	0.000000	67.555908
DRYB48NO	0.000000	60.699799
DRYB48IR	0.000000	223.362640
DRYB51NO	0.000000	91.719772
DRYB51IR	0.000000	67.128174
DRYB64NO	0.000000	41.389923
DRYB64IR	0.000000	85.648468
DRYB69NO	0.000000	93.059906
DRYB69IR	0.000000	248.150238
DRYB70NO	0.000000	75.160049
DRYB70IR	0.000000	226.584122
DRYB73NO	0.000000	55.969986
DRYB73IR	0.000000	251.654556
DRYB74NO	0.000000	2.789902
DRYB74IR	0.000000	60.989609
SUGBTNO	39271.000000	0.000000
SUGBTIR	0.000000	486.784424

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	98.839996
3)	0.000000	5.946856
4)	0.000000	582.029785
5)	0.000000	50.879990
6)	0.000000	117.239990
7)	0.000000	195.919769
8)	0.000000	620.620117
9)	0.000000	62.650146
10)	0.000000	173.489838
11)	39271.000000	0.000000

12)	0.000000	109.970001
13)	0.000000	163.369965
14)	0.000000	154.360001
15)	0.000000	150.729996
16)	0.000000	131.139999
17)	0.000000	211.509766

NO. ITERATIONS= 31

RANGES IN WHICH THE BASIS IS UNCHANGED:

		OBJ COEFFICIENT RANGES	
VARIABLE	CURRENT COEF	ALLOWABLE INCREASE	ALLOWABLE DECREASE
CORN40NO	149.719986	60.989609	50.879990
CORN40IR	332.819824	387.797852	INFINITY
CORN41NO	216.079987	2.789902	19.990143
CORN41IR	395.869873	307.852295	INFINITY
CORN42NO	294.759766	INFINITY	67.569672
CORN42IR	392.859863	312.232910	INFINITY
CORN43NO	436.959961	282.500244	INFINITY
CORN43IR	427.309814	512.183838	INFINITY
CORN46NO	141.500000	19.990143	INFINITY
CORN46IR	382.119873	278.906006	INFINITY
CORN48NO	272.329834	INFINITY	60.699799
CORN48IR	439.629883	248.979828	INFINITY
CORN51NO	98.839996	50.879990	67.128174
CORN51IR	390.969971	177.671631	INFINITY
CORN64NO	208.809998	INFINITY	41.389923
CORN64IR	394.439941	254.437286	INFINITY
CORN69NO	262.209961	INFINITY	93.059906
CORN69IR	434.569824	321.229004	INFINITY
CORN70NO	253.199997	INFINITY	75.160049
CORN70IR	432.989990	301.905029	INFINITY
CORN73NO	249.569992	INFINITY	55.969986
CORN73IR	399.179932	296.404297	INFINITY
CORN74NO	229.979996	INFINITY	2.789902
CORN74IR	381.169922	354.292725	INFINITY
SOYB40NO	9.299999	140.419983	INFINITY
SOYB40IR	173.399994	523.430420	INFINITY
SOYB41NO	56.699997	159.379990	INFINITY
SOYB41IR	249.929993	697.613037	INFINITY
SOYB42NO	59.799988	234.959778	INFINITY
SOYB42IR	221.569992	632.193848	INFINITY
SOYB43NO	264.149902	455.310059	INFINITY
SOYB43IR	257.309814	818.961426	INFINITY
SOYB46NO	44.259995	117.230148	INFINITY
SOYB46IR	204.479996	557.642334	INFINITY
SOYB48NO	80.000000	192.329834	INFINITY
SOYB48IR	251.869995	656.773193	INFINITY
SOYB51NO	2.299999	96.539993	INFINITY
SOYB51IR	250.319992	532.407959	INFINITY

SOYB64NO	37.269989	171.540009	INFINITY
SOYB64IR	178.839996	571.133789	INFINITY
SOYB69NO	71.459991	190.749969	INFINITY
SOYB69IR	245.659988	730.172363	INFINITY
SOYB70NO	62.519989	190.680008	INFINITY
SOYB70IR	236.339996	688.854492	INFINITY
SOYB73NO	79.229996	170.339996	INFINITY
SOYB73IR	268.969971	670.435059	INFINITY
SOYB74NO	45.039993	184.940002	INFINITY
SOYB74IR	227.789993	650.396729	INFINITY
DRYB40NO	231.219986	130.009766	INFINITY
DRYB40IR	985.649902	INFINITY	60.989609
DRYB41NO	427.589844	19.990143	2.789902
DRYB41IR	970.699951	111.043945	INFINITY
DRYB42NO	438.699951	67.569672	INFINITY
DRYB42IR	937.979980	133.240814	INFINITY
DRYB43NO	930.969971	INFINITY	282.500244
DRYB43IR	942.429932	291.829590	INFINITY
DRYB46NO	373.000000	INFINITY	19.990143
DRYB46IR	917.969971	67.555908	INFINITY
DRYB48NO	423.139893	60.699799	INFINITY
DRYB48IR	878.949951	223.362640	INFINITY
DRYB51NO	218.629990	91.719772	INFINITY
DRYB51IR	927.109863	67.128174	INFINITY
DRYB64NO	378.929932	41.389923	INFINITY
DRYB64IR	923.409912	85.648468	INFINITY
DRYB69NO	380.659912	93.059906	INFINITY
DRYB69IR	867.829834	248.150238	INFINITY
DRYB70NO	389.549805	75.160049	INFINITY
DRYB70IR	892.279785	226.584122	INFINITY
DRYB73NO	405.109863	55.969986	INFINITY
DRYB73IR	881.419922	251.654556	INFINITY
DRYB74NO	438.699951	2.789902	INFINITY
DRYB74IR	1004.919920	60.989609	INFINITY
SUGBTNO	680.869873	INFINITY	486.784424
SUGBTIR	753.089844	486.784424	INFINITY

RIGHTHAND SIDE RANGES

ROW	CURRENT RHS	ALLOWABLE INCREASE	ALLOWABLE DECREASE
2	392713.000000	39271.000000	4547.996090
3	1135704.000000	1126205.000000	1135703.000000
4	39271.000000	4547.996090	39271.000000
5	22366.000000	4547.996090	11549.769500
6	84910.000000	4547.996090	39271.000000
7	84161.000000	4547.996090	39271.000000
8	20713.000000	4547.996090	20713.000000
9	24506.000000	4547.996090	24506.000000
10	4034.000000	4547.996090	4034.000000
11	43819.000000	INFINITY	39271.000000
12	57902.000000	4547.996090	39271.000000
13	16191.000000	4547.996090	16191.000000

14	16274.000000	4547.996090	16274.000000
15	14939.000000	4547.996090	14939.000000
16	2898.000000	4547.996090	2898.000000
17	66761.000000	74184.187500	10725.769500

APPENDIX E

Appendix E

Linear Programming Model Output for the Cass River Watershed Crop Mix with All the Parameters at 75 Percent Confidence Level, While Assuming Unlimited Streamflow Supply

MAX - 32.01999 CORN40NO + 90.7 CORN40IR + 5.95 CORN41NO
+ 195.21999 CORN41IR + 20.04999 CORN42NO
+ 246.39999 CORN42IR + 255.50999 CORN43NO + 249.95
CORN43IR - 8.4 CORN46NO + 232.17 CORN46IR + 44.68999
CORN48NO + 274.33984 CORN48IR - 49.54999 CORN51NO
+ 235.21999 CORN51IR + 7.6 CORN64NO + 250.71999 CORN64IR
+ 63.73999 CORN69NO + 274.07983 CORN69IR + 52.42999
CORN70NO + 275.47998 CORN70IR + 57.89 CORN73NO +
243.34999 CORN73IR + 16.75 CORN74NO + 128.03 CORN74IR
- 67.42 SOYB40NO + 53.93999 SOYB40IR - 34.2 SOYB41NO +
125.51999 SOYB41IR - 34.81 SOYB42NO + 108.29999
SOYB42IR + 144.57999 SOYB43NO + 141.51999 SOYB43IR -
34.81 SOYB46NO + 75.07999 SOYB46IR - 33 SOYB48NO +
114.34 SOYB48IR - 61.98999 SOYB51NO + 124.60999
SOYB51IR - 52.31999 SOYB64NO + 58.17 SOYB64IR
- 33.59999 SOYB69NO + 105.28 SOYB69IR - 33.59999
SOYB70NO + 107.39999 SOYB70IR - 26.34999 SOYB73NO
+ 146.95999 SOYB73IR - 45.67999 SOYB74NO + 105.28
SOYB74IR - 8.11 DRYB40NO + 675.16992 DRYB40IR + 130.2
DRYB41NO + 680.6499 DRYB41IR + 146.34999 DRYB42NO
+ 641.28979 DRYB42IR + 659.1499 DRYB43NO
+ 641.48999 DRYB43IR + 113.06999 DRYB46NO + 639.5
DRYB46IR + 175.84999 DRYB48NO + 593.45996 DRYB48IR +
14.81 DRYB51NO + 658.62988 DRYB51IR + 81.57999
DRYB64NO + 629.52979 DRYB64IR + 140.37 DRYB69NO +
590.06982 DRYB69IR + 154.92 DRYB70NO + 606.31982
DRYB70IR + 157.90999 DRYB73NO + 607.40991 DRYB73IR +
118.64999 DRYB74NO + 700.08984 DRYB74IR + 351.81982
SUGBTNO + 418.44995 SUGBTIR

SUBJECT TO

2) CORN40NO + CORN40IR + CORN41NO + CORN41IR + CORN42NO
+ CORN42IR + CORN43NO + CORN43IR + CORN46NO + CORN46IR
+ CORN48NO + CORN48IR + CORN51NO + CORN51IR + CORN64NO
+ CORN64IR + CORN69NO + CORN69IR + CORN70NO + CORN70IR
+ CORN73NO + CORN73IR + CORN74NO + CORN74IR + SOYB40NO
+ SOYB40IR + SOYB41NO + SOYB41IR + SOYB42NO + SOYB42IR
+ SOYB43NO + SOYB43IR + SOYB46NO + SOYB46IR + SOYB48NO
+ SOYB48IR + SOYB51NO + SOYB51IR + SOYB64NO + SOYB64IR
+ SOYB69NO + SOYB69IR + SOYB70NO + SOYB70IR + SOYB73NO
+ SOYB73IR + SOYB74NO + SOYB74IR + DRYB40NO + DRYB40IR
+ DRYB41NO + DRYB41IR + DRYB42NO + DRYB42IR + DRYB43NO
+ DRYB43IR + DRYB46NO + DRYB46IR + DRYB48NO + DRYB48IR
+ DRYB51NO + DRYB51IR + DRYB64NO + DRYB64IR + DRYB69NO

```
 + DRYB69IR + DRYB70NO + DRYB70IR + DRYB73NO + DRYB73IR
 + DRYB74NO + DRYB74IR + SUGBTNO + SUGBTIR =    392713

 3) SUGBTNO + SUGBTIR <=   39271

 4) CORN40NO + CORN40IR + SOYB40NO + SOYB40IR + DRYB40NO
 +  DRYB40IR <=   22366

 5) CORN41NO + CORN41IR + SOYB41NO + SOYB41IR + DRYB41NO
 +  DRYB41IR <=   84910

 6) CORN42NO + CORN42IR + SOYB42NO + SOYB42IR + DRYB42NO
 +  DRYB42IR <=   84161

 7) CORN43NO + CORN43IR + SOYB43NO + SOYB43IR + DRYB43NO
 +  DRYB43IR <=   20713

 8) CORN46NO + CORN46IR + SOYB46NO + SOYB46IR + DRYB46NO
 +  DRYB46IR <=   24506

 9) CORN48NO + CORN48IR + SOYB48NO + SOYB48IR + DRYB48NO
 +  DRYB48IR <=   4034

10) CORN51NO + CORN51IR + SOYB51NO + SOYB51IR + DRYB51NO
 +  DRYB51IR <=   43819

11) CORN64NO + CORN64IR + SOYB64NO + SOYB64IR + DRYB64NO
 +  DRYB64IR <=   57902

12) CORN69NO + CORN69IR + SOYB69NO + SOYB69IR + DRYB69NO
 +  DRYB69IR <=   16191

13) CORN70NO + CORN70IR + SOYB70NO + SOYB70IR + DRYB70NO
 +  DRYB70IR <=   16274

14) CORN73NO + CORN73IR + SOYB73NO + SOYB73IR + DRYB73NO
 +  DRYB73IR <=   14939

15) CORN74NO + CORN74IR + SOYB74NO + SOYB74IR + DRYB74NO
 +  DRYB74IR <=   2898

16) DRYB40NO + DRYB40IR + DRYB41NO + DRYB41IR + DRYB42NO
 +  DRYB42IR + DRYB43NO + DRYB43IR + DRYB46NO + DRYB46IR
 +  DRYB48NO + DRYB48IR + DRYB51NO + DRYB51IR + DRYB64NO
 +  DRYB64IR + DRYB69NO + DRYB69IR + DRYB70NO + DRYB70IR
 +  DRYB73NO + DRYB73IR + DRYB74NO + DRYB74IR <=   66761
END
```

LP OPTIMUM FOUND AT STEP 22

OBJECTIVE FUNCTION VALUE

1) 132945120.

VARIABLE	VALUE	REDUCED COST
CORN40NO	0.000000	227.239975
CORN40IR	0.000000	104.519989
CORN41NO	0.000000	189.269974
CORN41IR	4142.000000	0.000000
CORN42NO	0.000000	226.350006
CORN42IR	84161.000000	0.000000
CORN43NO	20713.000000	0.000000
CORN43IR	0.000000	5.559998
CORN46NO	0.000000	240.569992
CORN46IR	24506.000000	0.000000
CORN48NO	0.000000	229.649857
CORN48IR	4034.000000	0.000000
CORN51NO	0.000000	284.769775
CORN51IR	43619.000000	0.000000
CORN64NO	0.000000	243.119980
CORN64IR	57902.000000	0.000000
CORN69NO	0.000000	210.339844
CORN69IR	16191.000000	0.000000
CORN70NO	0.000000	223.049988
CORN70IR	16274.000000	0.000000
CORN73NO	0.000000	185.459991
CORN73IR	14939.000000	0.000000
CORN74NO	0.000000	197.909927
CORN74IR	0.000000	86.629929
SOYB40NO	0.000000	262.639893
SOYB40IR	0.000000	141.279999
SOYB41NO	0.000000	229.419983
SOYB41IR	0.000000	69.699997
SOYB42NO	0.000000	281.209961
SOYB42IR	0.000000	138.100006
SOYB43NO	0.000000	110.930008
SOYB43IR	0.000000	113.990005
SOYB46NO	0.000000	266.979980
SOYB46IR	0.000000	157.090012
SOYB48NO	0.000000	307.339844
SOYB48IR	0.000000	159.999847
SOYB51NO	0.000000	297.209961
SOYB51IR	0.000000	110.610001
SOYB64NO	0.000000	303.039795
SOYB64IR	0.000000	192.549988
SOYB69NO	0.000000	307.679687

SOYB69IR	0.000000	168.799835
SOYB70NO	0.000000	309.079834
SOYB70IR	0.000000	168.079987
SOYB73NO	0.000000	269.699951
SOYB73IR	0.000000	96.389999
SOYB74NO	0.000000	260.339844
SOYB74IR	0.000000	109.379929
DRYB40NO	0.000000	688.759521
DRYB40IR	0.000000	5.479980
DRYB41NO	0.000000	550.449463
DRYB41IR	63863.000000	0.000000
DRYB42NO	0.000000	585.479492
DRYB42IR	0.000000	90.540283
DRYB43NO	0.000000	81.790039
DRYB43IR	0.000000	99.449951
DRYB46NO	0.000000	604.529541
DRYB46IR	0.000000	78.100098
DRYB48NO	0.000000	583.919434
DRYB48IR	0.000000	166.309814
DRYB51NO	0.000000	705.839600
DRYB51IR	0.000000	62.020020
DRYB64NO	0.000000	654.569580
DRYB64IR	0.000000	106.620117
DRYB69NO	0.000000	619.139404
DRYB69IR	0.000000	169.439941
DRYB70NO	0.000000	605.989502
DRYB70IR	0.000000	154.590088
DRYB73NO	0.000000	570.869629
DRYB73IR	0.000000	121.370117
DRYB74NO	0.000000	581.439453
DRYB74IR	2898.000000	0.000000
SUGBTNO	0.000000	66.630127
SUGBTIR	39271.000000	0.000000

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	195.219986
3)	0.000000	223.229965
4)	22366.000000	0.000000
5)	16905.000000	0.000000
6)	0.000000	51.180008
7)	0.000000	60.290009
8)	0.000000	36.950012
9)	0.000000	79.119858
10)	0.000000	40.000000
11)	0.000000	55.500000
12)	0.000000	78.859848
13)	0.000000	80.259995
14)	0.000000	48.130005
15)	0.000000	19.439941
16)	0.000000	485.429687

NO. ITERATIONS= 22

RANGES IN WHICH THE BASIS IS UNCHANGED:

VARIABLE	CURRENT COEF	OBJ COEFFICIENT RANGES ALLOWABLE INCREASE	ALLOWABLE DECREASE
CORN40NO	-32.019989	227.239975	INFINITY
CORN40IR	90.699997	104.519989	INFINITY
CORN41NO	5.950000	189.269974	INFINITY
CORN41IR	195.219986	36.950012	69.699997
CORN42NO	20.049988	226.350006	INFINITY
CORN42IR	246.399994	INFINITY	51.180008
CORN43NO	255.509995	INFINITY	5.559998
CORN43IR	249.949997	5.559998	INFINITY
CORN46NO	-8.400000	240.569992	INFINITY
CORN46IR	232.169998	INFINITY	36.950012
CORN48NO	44.689987	229.649857	INFINITY
CORN48IR	274.339844	INFINITY	79.119858
CORN51NO	-49.549988	284.769775	INFINITY
CORN51IR	235.219986	INFINITY	40.000000
CORN64NO	7.599999	243.119980	INFINITY
CORN64IR	250.719986	INFINITY	55.500000
CORN69NO	63.739990	210.339844	INFINITY
CORN69IR	274.079834	INFINITY	78.859848
CORN70NO	52.429993	223.049988	INFINITY
CORN70IR	275.479980	INFINITY	80.259995
CORN73NO	57.889999	185.459991	INFINITY
CORN73IR	243.349991	INFINITY	48.130005
CORN74NO	16.750000	197.909927	INFINITY
CORN74IR	128.029999	86.629929	INFINITY
SOYB40NO	-67.419998	262.639893	INFINITY
SOYB40IR	53.939987	141.279999	INFINITY
SOYB41NO	-34.199997	229.419983	INFINITY
SOYB41IR	125.519989	69.699997	INFINITY
SOYB42NO	-34.809998	281.209961	INFINITY
SOYB42IR	108.299988	138.100006	INFINITY
SOYB43NO	144.579987	110.930008	INFINITY
SOYB43IR	141.519989	113.990005	INFINITY
SOYB46NO	-34.809998	266.979980	INFINITY
SOYB46IR	75.079987	157.090012	INFINITY
SOYB48NO	-33.000000	307.339844	INFINITY
SOYB48IR	114.339996	159.999847	INFINITY
SOYB51NO	-61.989990	297.209961	INFINITY
SOYB51IR	124.609985	110.610001	INFINITY
SOYB64NO	-52.319992	303.039795	INFINITY
SOYB64IR	58.169998	192.549988	INFINITY
SOYB69NO	-33.599991	307.679687	INFINITY
SOYB69IR	105.279999	168.799835	INFINITY
SOYB70NO	-33.599991	309.079834	INFINITY
SOYB70IR	107.399994	168.079987	INFINITY
SOYB73NO	-26.349991	269.699951	INFINITY

SOYB73IR	146.959991	96.389999	INFINITY
SOYB74NO	-45.679993	260.339844	INFINITY
SOYB74IR	105.279999	109.379929	INFINITY
DRYB40NO	-8.110000	688.759521	INFINITY
DRYB40IR	675.169922	5.479980	INFINITY
DRYB41NO	130.199997	550.449463	INFINITY
DRYB41IR	680.649902	19.439941	5.479980
DRYB42NO	146.349991	585.479492	INFINITY
DRYB42IR	641.289795	90.540283	INFINITY
DRYB43NO	659.149902	81.790039	INFINITY
DRYB43IR	641.489990	99.449951	INFINITY
DRYB46NO	113.069992	604.529541	INFINITY
DRYB46IR	639.500000	78.100098	INFINITY
DRYB48NO	175.849991	583.919434	INFINITY
DRYB48IR	593.459961	166.309814	INFINITY
DRYB51NO	14.809999	705.839600	INFINITY
DRYB51IR	658.629883	62.020020	INFINITY
DRYB64NO	81.579987	654.569580	INFINITY
DRYB64IR	629.529785	106.620117	INFINITY
DRYB69NO	140.369995	619.139404	INFINITY
DRYB69IR	590.069824	169.439941	INFINITY
DRYB70NO	154.919998	605.989502	INFINITY
DRYB70IR	606.319824	154.590088	INFINITY
DRYB73NO	157.909988	570.869629	INFINITY
DRYB73IR	607.409912	121.370117	INFINITY
DRYB74NO	118.649994	581.439453	INFINITY
DRYB74IR	700.089844	INFINITY	19.439941
SUGBTNO	351.819824	66.630127	INFINITY
SUGBTIR	418.449951	INFINITY	66.630127

RIGHTHAND SIDE RANGES

ROW	CURRENT RHS	ALLOWABLE INCREASE	ALLOWABLE DECREASE
2	392713.000000	16905.000000	4142.000000
3	39271.000000	4142.000000	16905.000000
4	22366.000000	INFINITY	22366.000000
5	84910.000000	INFINITY	16905.000000
6	84161.000000	4142.000000	16905.000000
7	20713.000000	4142.000000	16905.000000
8	24506.000000	4142.000000	16905.000000
9	4034.000000	4142.000000	4034.000000
10	43819.000000	4142.000000	16905.000000
11	57902.000000	4142.000000	16905.000000
12	16191.000000	4142.000000	16191.000000
13	16274.000000	4142.000000	16274.000000
14	14939.000000	4142.000000	14939.000000
15	2898.000000	63863.000000	2898.000000
16	66761.000000	4142.000000	63863.000000

APPENDIX F

Appendix F

Linear Programming Model Output for the Cass River Watershed Crop Mix (Streamflow at 75 percent exceedence level, actual non-irrigated crop yields at the 75 percent confidence level and irrigated crop yields (1987-1990))

```
MAX      46.96999 CORNNO + 233.18999 CORNIR + 14.12 SOYBNO
         +107.09999 SOYBIR + 96.71999 DRYBNO +
          300.08984 DRYBIR + 151.89 SUGBTNO +
          370.70996 SUGBTIR

SUBJECT TO

        2) CORNNO + CORNIR + SOYBNO + SOYBIR + DRYBNO + DRYBIR
           + SUGBTNO + SUGBTIR =     392713

        3) 135 CORNIR + 109 SOYBIR + 77 DRYBIR + 152 SUGBTIR
           = 543489

        4) SUGBTNO + SUGBTIR <= 39271

        5) DRYBNO + DRYBIR <= 66761

END


LP OPTIMUM FOUND AT STEP       4

        OBJECTIVE FUNCTION VALUE

        1)     27322832.0
```

VARIABLE	VALUE	REDUCED COST
CORNNO	286680.937000	0.000000
CORNIR	0.000000	170.337372
SOYBNO	0.000000	32.849976
SOYBIR	0.000000	227.756958
DRYBNO	59702.699200	0.000000
DRYBIR	7058.296870	0.000000
SUGBTNO	39271.000000	0.000000
SUGBTIR	0.000000	182.637543

ROW	SLACK OR SURPLUS	DUAL PRICES
2)	0.000000	46.969986
3)	0.000000	2.641167
4)	0.000000	104.920013
5)	0.000000	49.750000

NO. ITERATIONS= 4

RANGES IN WHICH THE BASIS IS UNCHANGED:

OBJ COEFFICIENT RANGES

VARIABLE	CURRENT COEF	ALLOWABLE INCREASE	ALLOWABLE DECREASE
CORNNO	46.969986	49.750000	32.849976
CORNIR	233.189987	170.337372	INFINITY
SOYBNO	14.120000	32.849976	INFINITY
SOYBIR	107.099991	227.756958	INFINITY
DRYBNO	96.719986	92.520386	49.750000
DRYBIR	300.089844	INFINITY	92.520386
SUGBTNO	151.889999	INFINITY	104.920013
SUGBTIR	370.709961	182.637543	INFINITY

RIGHTHAND SIDE RANGES

ROW	CURRENT RHS	ALLOWABLE INCREASE	ALLOWABLE DECREASE
2	392713.000000	INFINITY	286680.937000
3	543489.000000	4597108.000000	543488.937000
4	39271.000000	286680.937000	39271.000000
5	66761.000000	286680.937000	59702.699200

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