



Incorporation of Agricultural Risk into Water Resource Planning Models

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Technical Report #25

INCORPORATION OF AGRICULTURAL RISK
INTO WATER RESOURCE PLANNING MODELS

by

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OWRR Grant No. 14-01-0001-1600

January 1970

PREFACE

This is the final draft of a report submitted to the Office of Water Resources Research by the Institute of Statistics, Texas A&M University. This report represents work conducted under Project C-1 227, OWRR entitled "Introduction of Risk and Uncertainty Concepts to Optimization of Water Resource System Design." In its present form, this manuscript was submitted to the Graduate College of Texas A&M University as a Doctor of Philosophy dissertation in Agricultural Economics.

The author wishes to express his gratitude to Dr. R. J. Freund, project leader, and Dr. M. R. Godwin for their leadership and guidance throughout the undertaking of this study. Thanks are also due Dr. W. L. Bathke for the initial work on the project which provided the basis for the research effort reported here.

TABLE OF CONTENTS

CHAPTER		Page
I	The Problem	1
	An Overview	1
	Earlier Simulations of Water Resource Systems	4
	The Treatment of Risk	7
	Objectives of this Study	10
II	The System	14
	Introduction to the System	14
	Basic Properties of the System	16
	The Simulation Model	19
	Total Available Water	19
	The Farmer's Decision Process	24
	Total Project Evaluation	26
	Operations of the Simulation Model	28
	Basic Assumptions and Constraints Governing the Model	28
	Capabilities of the Model	32
III	Basic Data Inputs to the Model	37
	Cost Data for the System	37
	The Hydrologic Data	39
	Crop Production, Costs and Returns Data	40
IV	Results of the Simulation	55
	The Primary Net Benefit Response Surface	56
	The Interaction Between the Target Delivery and Planned Acres Irrigated	62
	The Effects of Risk on the Primary Net Benefits	66
	Marginal Value Product Returns Response Surface	73
	The Effects of Risk on the Marginal Value Product Net Returns	76
	Comparison of Primary Net Benefits Approach and the Marginal Value Product Approach	84
V	Summary	87
	Limiting Assumptions	89
	Analytical and Data Limitations	90
	Conclusions Concerning Future Investigation	93

REFERENCES	Page 95
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APPENDIX A

Stream Flow of South Concho River at San Angelo, in 1,000 Acre Feet.	99
Effective Precipitation at San Angelo, in Inches	101
Effective Evaporation Rate at San Angelo, in Feet Per Unit Surface Area.	103

APPENDIX B

Simulation Results for $\alpha = .00005$ and Total Annual Water Target = 5.0 Ft. Per Year.	106
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LIST OF TABLES

Table	Page
1. Representative Cotton Production Costs and Returns, Tom Green County, Texas	42
2. Representative Grain Sorghum Production Costs and Returns, Tom Green County, Texas, 1967.	43
3. Representative Alfalfa Costs and Returns, Tom Green County, Texas, 1967	45
4. Representative Oat Production Costs and Returns, Tom Green County, Texas, 1967	46
5. Representative Crop Yield Responses to Varying Levels of Total Water Available Per Year	47
6. Cotton Net Returns (N) as a Function of Total Annual Water	53
7. Grain Sorghum Net Returns (N) as a Function of Total Annual Water (W).	53
8. Oats and Alfalfa Net Returns (N) as a Function of Total Annual Water (W).	54
9. Acres Used and Net Returns of Enterprise Making Up Solution Points I and II.	65
10. The Effects of the Different Levels of Farmers Aversion to Risk on the Design Variables.	71

LIST OF FIGURES

Figure	Page
1. Schematic Representation of the Water Resource System Simulated in this Study	15
2. Cotton Net Returns as a Function of Total Annual Water.	50
3. Grain Sorghum Net Returns as a Function of Total Annual Water	51
4. Oats and Alfalfa Net Returns as a Function of Total Annual Water	52
5. Annual Primary Net Benefits (in \$1,000) as a Function of Delivery Target (T) and Planned Acres Irrigated (I) Using a Risk Aversion Constant of $\alpha = 0.00005$ and Reservoir Capacity of 150,000 Ac. Ft.	58
6. Annual Primary Net Benefits (in \$1,000) as a Function of Reservoir Capacity (R) and Delivery Target (T) Using a Risk Aversion Constant of $\alpha = 0.00005$ and Planned Acres Irrigated = 6,000.	59
7. Annual Primary Net Benefits (in \$1,000) as a Function of Reservoir Capacity (R) and Planned Acres Irrigated (I) Using a Risk Aversion Constant of $\alpha = 0.00005$ and a Delivery Target = 5.667 Ac. Ft.	60
8. Annual Net Returns Per Acre for Cotton Irrigated Once from the Simulated Points I and II and Annual Rainfall for the 39-Year Period Used in the Model.	64
9. Annual Primary Net Benefits (in \$1,000) as a Function of Target (T) and Planned Acres Irrigated (I) Using A Risk Aversion Constant of $\alpha = 0$ and a Reservoir Capacity of 157,000 Ac. Ft.	67
10. Annual Primary Net Benefits (in \$1,000) as a Function of Delivery Target (T) and Planned Acres Irrigated (I) Using a Risk Aversion Constant of $\alpha = 0.0001$ and Reservoir Capacity of 150,000 Ac. Ft.	69

Figure	Page
11. Annual Primary Net Benefits (in \$1,000) as a Function of Delivery Target (T) and Planned Acres Irrigated (I) Using a Risk Aversion Constant of $\alpha = 0.00002$ of Reservoir Capacity of 150,000 Ac. Ft.	70
12. Marginal Value Product Net Returns (in \$1,000) as a Function of Delivery Target (T) and Planned Acres Irrigated Using a Risk Aversion Constant of $\alpha = 0.00005$ and a Reservoir Capacity of 150,000 Ac. Ft.	75
13. Marginal Value Product Net Returns (in \$1,000) as a Function of Delivery Target (T) and Reservoir Capacity (R) Using a Risk Aversion Constant of $\alpha = 0.00005$ and Planned Acres Irrigated = 6,000	77
14. Marginal Value Product Net Returns (in \$1,000) as a Function of Reservoir Capacity (R) and Planned Acres Irrigated (I) Using a Risk Aversion Constant of $\alpha = 0.00005$ and a Delivery Target = 5.667 Ac. Ft.	78
15. Marginal Value Product Net Returns (in \$1,000) as a Function of Delivery Target (T) and Planned Acres Irrigated (I) Using a Risk Aversion Constant of $\alpha = .0$ and a Reservoir Capacity of 180,000 Ac. Ft.	80
16. Marginal Value Product Net Returns (in \$1,000) as a Function of Delivery Target (T) and Planned Acres Irrigated (I) Using a Risk Aversion Constant of $\alpha = .0001$ and a Reservoir Capacity of 180,000 Ac. Ft.	81
17. Marginal Value Product Net Returns (in \$1,000) as a Function of Delivery Target (T) and Planned Acres Irrigated (I) Using a Risk Aversion Constant of $\alpha = 0.00002$ and a Reservoir Capacity of 150,000 Ac. Ft.	83

CHAPTER I

The Problem

An Overview

Federal, state and local planners in the United States have come to realize that our rapidly growing population, and the increased agricultural, municipal, recreational and industrial expansion caused by this population growth, is increasing the demand for water at an alarming rate. With this in mind, the U. S. Congress has instructed our federal agencies to investigate "The needs and possibilities for all significant resource uses and purposes of development, including, but not limited to, domestic, municipal, agricultural and industrial uses of water, ... and all relevant means (including nonstructural as well as structural measures) singly, in combination, or in alternative combinations reflecting different choice patterns for providing such uses and purpose" [25, p. 3].*

The major means of meeting this increased demand for water is the construction of reservoirs on rivers and streams. These facilities are usually financed by public funds and thus should be well planned to insure economic efficiency and maximization of social welfare. Included among the more important questions that must be

*The citations on this and the following pages follow the style of the American Journal of Agricultural Economics.

answered in the planning stage are: (a) in what river basins and at what points in these basins should impoundment structures be located, (b) what purposes or needs are these structures to meet and (c) what size structures shall be built? For facilities financed by the federal government, most of these decisions are made by the Congress aided by information furnished by the Corps of Engineers. The primary factors considered in making these decisions are economic efficiency, income redistribution and political expediency [12].

Most planners consider the criterion of economic efficiency as the most important and much effort is expended in studying this criterion by the Corps of Engineers for each proposed water resource project. For the most part, economic efficiency is determined by benefit-cost analysis and is measured by the benefit-cost ratio. The benefits are those annual incomes that accrue to society from the operation of a project. These include not only the primary, or direct incomes, called primary benefits, but usually in addition include indirect incomes, called secondary benefits. The costs are the annual repayment of construction capital, discounted over the assumed life of the project, as well as annual operation and maintenance costs incurred in the operation of a project. Net benefits, or the difference between benefits and costs, are sometimes used instead of the benefit-cost ratio as a measure of economic efficiency.

Planners, however, have realized that there are many problems associated with the way benefit-cost analyses have been conducted in the past, particularly in regard to large river basin projects. Of primary interest are the problems of determining how big a reservoir should be built, what purposes are to be served by it and how much annual benefit will accrue to society from its operation. In order to alleviate some of these problems, planners have been experimenting with the use of systems analysis techniques as tools to aid in more efficient and realistic benefit-cost analyses. Systems analysis techniques are helpful because they offer in any one, or combinations of more than one, part of the system.

Generally, there are two types of systems analysis techniques that can be used in water resource system planning: analytic models and simulation models. Analytic models entail sets of equations whose solutions yield optimal values for design variables.¹ The use of the analytic model involves a drastic simplification of the real situation in order to restrict the system of equations to existing solution capabilities. Thus, analytic models have usually been used for analyzing only a part of a river basin.

Simulation involves the conceptualizing, building and operation of a model, usually mathematical, designed to represent the dynamic environment of the situation under consideration. The use of

¹For a good review of the work that has been done in river basin planning using analytical models see [9, pp. 4-7].

environment of the situation under consideration. The use of simulation models as a technique for solving problems in water resource system design began with the development of modern electronic computers. With expanded computational capacity, a number of very sophisticated simulation models of water resource systems have been developed and used. These models entail fewer restricting and simplifying assumptions than analytic models.

One important shortcoming of the simulation technique is the lack of an internal algorithm for optimization. Therefore, a technique for sampling part of all the possible combinations of the relevant variables in a system must be incorporated to facilitate an optimizing procedure. In spite of this shortcoming, the simulation technique is used in the study presented here because of its excellent ability to realistically represent complex water resource systems.

Earlier Simulations of Water Resource Systems

Early simulation models of river basin systems include a simulation of the Nile River Valley Plain conducted by Morrice and Allan [21]. The objective of this work was to determine the optimal combination of project structures and operations which would maximize the use of irrigation water. Also, the Columbia River Basin was simulated by Brown in order to evaluate power outputs of a large number of alternative system designs [7]. Britton conducted a simulation analysis which attempted the integration of Glen Canyon Dam into the Colorado River System [6].

The best known model is that of the Harvard Water Program [19, pp. 324-458] in which a hypothetical river basin system was simulated. It involved 12 design variables consisting of reservoirs, power plants, irrigation works, target output for irrigation and electrical energy and specified allocations of reservoir capacity for flood control. The economic benefits of the system were determined on the basis of use and control of the water moving through the system. In addition to sampling from the many combinations of design variables, steepest ascent procedures were also used to facilitate the search for maximized net benefits. In addition to its original study [19], the Harvard Water Program undertook the development of a computer model of the Delaware River Basin [13, 24]. The multi-purpose system included water for municipal use, dilution-flow operations, water for recreation, flood control and water for electric power generation. The model used many of the concepts and approaches developed in the original simulation. The Harvard Water Program's simulation models, as well as most subsequent simulation models of river basin systems, included risk in the form of variable stream flow into the system.

Other studies include a comprehensive simulation of the Susquehanna River Basin developed by Battelle Memorial Institute [10]. The study was concerned with the economic interrelations existing in the river basin and attempted to delineate the factors influencing the economic growth of the area. To do this, the entire area was broken down into subregions, each of which was

described by a series of equations which related the inter-relations and feedbacks of three major factor groups: (a) size and distribution of the population, (b) kind and level of employment and (c) water availability and control. The sub-factors concerning water were water quality, water supply (agricultural, urban and industrial), water for recreation, flood control and water for electric power generation.

In a study of the Culapoola River Basin, Halter and Miller tested the applicability of the computer simulation technique to the planning, development and evaluation of river basin projects [9]. They studied five preselected combinations of reservoir size and channel improvement projects and evaluated the benefits accruing from these five combinations with respect to improved fish life, irrigation, drainage of farm land and flood control. Their model incorporated a simulated variable stream flow into the system.

Recently, Bathke [5] developed a simulation model of a simplified river basin, the South Concho near San Angelo, Texas. The design variables included in the model were a reservoir, an irrigation project, target output for irrigation and specific measurement of shortages due to highly variable stream inflow. This model was later expanded to include all of the design variables mentioned above, plus target output for municipal water supply and allowances for additional hydrologic risk due to the variability of rainfall and evaporation [4].

The Bathke model allowed for the computation of total net benefits as a function of reservoir capacity and number of acres in the irrigation project and included specific loss functions that introduced negative benefits when target outputs were not met. Using this model the system was simulated using actual flow data for a 39-year period and the resulting total net benefits were calculated for each of several reservoir capacities and irrigation project sizes. Thus, the total net benefits accruing from each of the specific combinations of reservoir capacity and irrigation project size were combined to form a response surface. From this response surface the optimal combination of reservoir capacity and irrigation project size were obtained by selecting the maximum total net benefit combination.

The Treatment of Risk

Although many river basin simulation studies incorporating several design variables have been completed in recent years, few, if any, have dealt adequately with the problem of risk that is inherent in any water resource system. The term risk, as used in this study, was defined by Knight as measurable uncertainty [16]. That is, a variable is said to be subject to risk if the level at which it occurs in a particular time period is governed by a particular probability distribution for which the mean and variance are known.

Risk elements usually enter a water resource system planning problem in two forms. First, there are hydrologic risk elements such as variable stream flows, evaporation rates and rainfall. The second form of risk is economic and is usually expressed as price variations. These risk elements are important because the benefits and costs associated with a particular water resource system are dependent to a great extent on the amount of stream flow into the system, the rate of evaporation and the amount of rainfall. Also, if the system is designed to furnish irrigation water to farms, the prices that the farmers receive for their crops and the prices that they pay for their production factors have considerable effect on the amount of benefits accruing to the system. Obviously then, planners of water resource systems should try to assess the effects of these various risk elements and incorporate these effects into the planning model.

Those studies which have dealt with the risk elements in water resource system planning have incorporated the effects of hydrologic risk on the design variables from the viewpoint that only the system planners could react to the effects of the risk elements. These studies ignored the fact that the users of the water from the system might also react to the risk elements in such a way as to affect the optimum level of the design variables. For example, one of the important findings in the Bathke study [4, 5] was that the optimal levels of the design variables for the system considered were such

that delivery of irrigation water would not be guaranteed with 100 percent certainty due to the variable stream inflow. Bathke assumed, however, that the farmers in the irrigation district could not react to this fact. That is, they planned their farm production as if water would be delivered with certainty. Bathke assumed only that, in years when shortages actually occurred, the farmers' incomes were decreased by a predetermined amount.

Economists, however, have long realized that in some cases people react differently to risk situations than they react to situations where outcomes are known with 100 percent certainty. Therefore, the reaction of a farmer to a particular degree of variation in income, due to variations in water availability, sometimes results in altered production practices. These altered practices may decrease the farmer's average income, while lessening the severity of losses associated with water shortages. These alterations in production practices are affected by such things as a farmer's financial ability to survive an income loss, his psychological willingness to take chances and the amount of possible loss that he thinks he might have to incur due to a water shortage. Thus, the reactions of farmers to these risk elements might affect the optimal system design characteristics. This prospect is the genesis of the study proposed here.

Objectives of this Study

When considering a complex and costly water resource system it is important that every effort be made to design and construct the system so as to maximize economic efficiency. This is necessary in order to be sure that society gets the most possible benefits for its expenditure. Since there are many possible combinations of reservoir sizes and uses of water that could be incorporated into a system, planning models are used to help alleviate this problem. For example, through the use of a simulation planning model, it is possible for the system planners to see the effects of many more of the combinations of levels of the design variables than they could without the model. Therefore, a necessary part of the objective of this study is to develop a simulation model that allows planners to examine all feasible combinations of levels of the design variables for a system. Likewise, the model should facilitate the selection of the optimal combination of these levels to insure maximum economic efficiency.

In the development of a simulation planning model this study is particularly concerned with incorporating the full effects of risk into a water resource system model. This incorporation of risk is designed in such a way that the effects of risk on the optimal levels of the design variables can be evaluated. These effects of the risk elements on the operation of the system necessarily include the water users' reactions to risk.

The risk elements considered in this study are hydrologic in nature. That is, this study is concerned with only that risk which arises from the variations in the amount of total water available for crop production. These variations are caused by variations in stream inflow to the reservoir, evaporation from the reservoir and rainfall on the irrigation development.

The amount of water available for crop production, and its variation, however, are manipulated somewhat by changing the levels of certain design variables of the system. These design variables are the number of acres that the system planners will furnish with irrigation water, the amount of water that will be furnished to each irrigated acre and the capacity of the reservoir. Thus, in a computational sense, the objective of this study is to find the combination of levels of these design variables that maximizes the economic efficiency of the water resource system.

In order to find the optimal combination of levels of the design variables, many different combinations must be simulated and an indication of the economic efficiency of the system for each combination must be obtained. From an economic standpoint, there are two basic approaches that can be taken to obtain an indication of the economic efficiency of the system. Both approaches are considered in this study.

The first is the traditional approach of trying to maximize the net benefits, or the benefit-cost ratio. This approach entails development of a function to evaluate the net benefits from the

system for each possible combination of levels of the design variables. Then, by evaluating a relevant set of possible combinations, the combination of levels of the design variables producing the maximum net benefits can be selected. This approach is basically the same as those used in several previous studies [4, 5, 13, 19, 24].

The second approach is to set the system up in the manner of a business firm whose purpose is to maximize profits, or minimize losses. If the possibility of pricing each unit of water differently is ignored, then a uniform price for the water must be determined. From economic theory, we know that a business firm cannot afford to pay more for a factor of production than the factor will return to it in the form of additional product revenue. Thus, one price that would be reasonable would be the marginal value product of the water in use. This price has an advantage in that it allows the irrigation farmers to allocate the water to its best use without regard to its price. This is true because the marginal value product is determined at the margin after all of the available water is utilized to its maximum potential. It should be noted, however, that if all of the water supplied to the farms is priced at the marginal value product of the last unit used, the system planners will not receive the full value for all the water. This is due to the fact that the last unit of irrigation water used does not contribute as much to total revenue as the units used prior to it. This additional value, the difference between the value of the last unit

and all the prior units, will instead accrue to the farm firms. This problem could conceivably be eliminated by charging a price for the water equal to its average value product, or through differential pricing. Such pricing schemes, however, would introduce considerable computational difficulties. That is, the farm firms would then have to consider the price of each additional unit of water separately before deciding to use it. Because of these complications it was decided that the marginal value product of water in use would be used as the price for all water supplied to the irrigation farms in this study.

The marginal value product approach is thus reduced to a process of determining the total returns accruing to the system from the sale of irrigation water priced at its final marginal value product in use on the farms. From these total returns are subtracted the costs of the system leaving the net returns as the remainder. These net returns are determined for each combination of levels of the design variables considered, thus allowing the selection of the combination for which the marginal value product net returns are maximized.

CHAPTER II

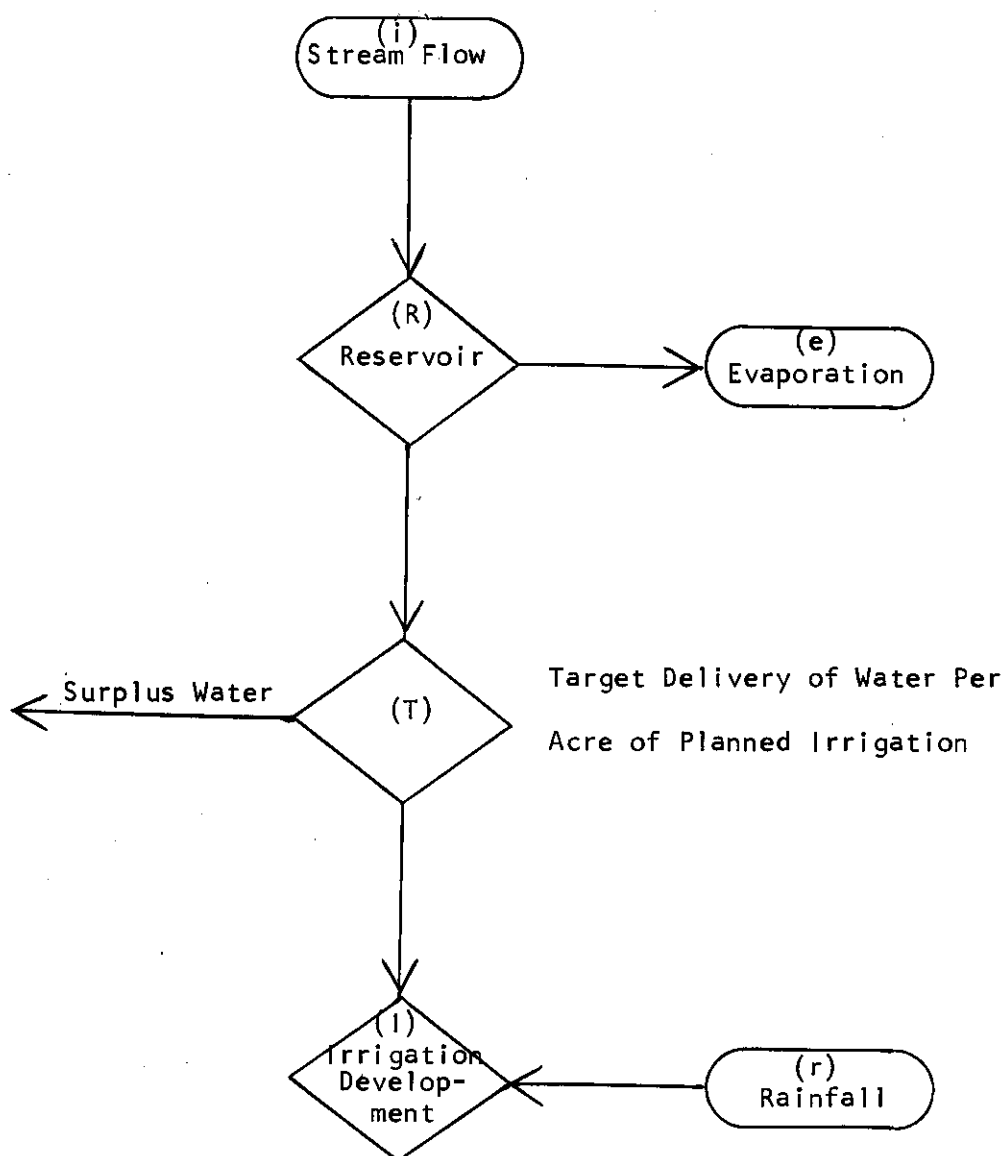
The System

Introduction to the System

The system considered in this study consists of a reservoir and irrigation development and is represented schematically in Figure 1. The design variables for which optimal sizes or levels are to be determined are: the reservoir capacity (R), in acre feet; the number of acres that are to be furnished with irrigation water (I); and the planned total amount of water to be furnished to each irrigated acre per year including rainfall, or, target water delivery (T), in acre feet per year. This system is also characterized by three hydrologic risk elements which are exogenous to the system. They are: the stream flow into the reservoir (i); the rate at which water evaporates from the reservoir (e); and the amount of rain that falls on each acre in the irrigation district (r). These exogenously determined risk variables exert considerable influence on the net benefits that might be obtained under the various combinations of levels of R , I and T .

Starting with a specific level of R , I and T , this model provides, using the actual inflow, evaporation and rainfall data for a 39-year period, a particular pattern of water deliveries to each farm in the irrigation district. It is assumed that the farmers know the characteristics or probability distributions of the water deliveries and other relevant information regarding typical

Fig. 1.--Schematic representation of the water resource system simulated in this study



agricultural operations of the area, and that they can determine a set of crop enterprises that will provide an optimal balance between the total income to the farm and the variation of that income. These crop enterprises include several different crops as well as different amounts of irrigation for each crop.

This particular combination of reservoir characteristics and resulting farm plans is simulated, over the same 39-year period, to determine the total net benefits of the entire system. These total net benefits are the difference between the total farm returns minus the costs of the reservoir and irrigation development, and the total farm returns to the area without any supplemental irrigation. This particular simulation is performed to provide net benefits for various combinations of levels of R, I, and T. A response surface of these net benefits is then estimated from these simulation points to determine the optimal combination of levels of the design variables.

Basic Properties of the System

As can be seen in Figure 1 this water resource system consists of one reservoir on a river for which the only use made of the impounded water is to provide irrigation water to one irrigation development. The maximum size of the irrigation development used in this study is 20,000 acres. This is necessary because much of the basic data for this study comes from the Twin Buttes Reservoir Project [27] for which only 20,000 acres of land are suitable for irrigation. The 20,000 acre irrigation development is assumed to

be made up of 60 farms of 333.3 acres each. This farm size is quite typical of both the dryland and irrigated farms in the region.

The Twin Buttes site allows for an extremely wide range of reservoir capacities; up to approximately 500,000 acre feet. Preliminary analyses, however, indicated that reservoir capacities greater than 300,000 acre feet would be irrelevant for irrigation purposes because of the limited amount of stream flow into the system. Hence, the largest reservoir capacity considered in this study is 300,000 acre feet.

The largest target amount of water considered, 5.67 acre feet per year, exceeds, by a considerable margin, both the amount per acre that can possibly be utilized by the irrigated crops, and the total amount of water that the system can conceivably furnish each irrigated acre 100 percent of the time. This large target is needed, however, because the model allows the irrigation farmers to allocate their water in a different manner than is assumed by the water system managers when they allocate it. Also, it should be noted that in considering the amount of water needed at any one particular time, the amount of rainfall for the same time period is considered to furnish part of the water requirement.

Each of the 60 farms in the irrigation district is assumed to produce one or a combination of four basic crops; grain sorghum, cotton, oats and alfalfa. These four crops are the ones most commonly found on both the dryland and irrigated farms in the region. Because of existing government programs and to comply with

production practices common to the area the acreages of cotton and grain sorghum are restricted to a maximum of 73 and 133 acres respectively for each of the 333.3 acre farms.

The farmers use the available water and other resources to maximize their income. In so doing, they may use the available water in a variety of different ways. For example, if the reservoir-irrigation planners provide for four feet of total available water for half of the acres in the development (10,000 acres or 166.7 acres per farm) the farmers may use it to intensively irrigate only 100 acres and farm the rest without supplemental water. Thus, it was necessary to define separate crop production enterprises for various irrigation intensities, including no irrigation, for each of the four crops. Thus, the four crops were broken down into 12 enterprises: (a) four different cotton production enterprises, dryland cotton, cotton irrigated one, two and three times; (b) five grain sorghum production enterprises, dryland grain sorghum, grain sorghum irrigated one, two, three and four times; (c) two oat production enterprises, dryland oats and irrigated oats; and (d) one alfalfa production enterprise. From these 12 enterprises the irrigation farmers can choose a combination of enterprises which utilizes no irrigation water, or a combination which utilizes a large amount of irrigation water.

The Simulation Model

Total Available Water

The simulation model is designed to evaluate the consequences of the system being constructed and operated at a particular combination of levels of the design variables, R, I and T, for the period for which data are available for these three risk variables: stream inflow to the system (i), the rate of evaporation of water out of the reservoir (e) and the amount of rainfall in the irrigation development (r). The available data for these three risk variables consists of 39 years, or 468 consecutive monthly records, for the years 1916 through 1954 (see Appendix A).

In the following algebraic representation of the simulation model the subscript y will represent yearly totals or variables and t will represent monthly totals. The first step in the model is to compute the amount of water demanded from the reservoir for each month. To do this, the diversion demand for the month can be determined through the equation:

$$D_t = 1.5 (C_t T - r_t) I \quad (1)$$

where

D_t = the amount of water to be diverted from the reservoir to the irrigation district in thousands of acre feet in month t,

C_t = the percent of the annual consumptive demand of the crops needed in the month t,

r_t = rainfall in feet for month t,

1.5 = a factor to account for conveyance losses,

T = the total annual amount of water, including both irrigation and rainfall, in acre feet, that the system will try to furnish each acre that it plans to irrigate, and

I = total acres, in thousands, that the system will try to furnish with the target (T) amount of water.

Next, the level of the reservoir for the first month is defined as

$$L_1 = R \quad (2)$$

where

L_1 = the level of the reservoir for the first month, and

R = the capacity of the reservoir in thousands of acre feet.

The amount of evaporation from the reservoir for the month is a function of the evaporation rate and the surface area and can be determined by either

$$E_t = e_t (.75 + .05 L_t), L_t \leq 11,$$

or

$$E_t = e_t (-.0121 + .1958 L_t - .0038 L_t^2 - .002 L_t^3), L_t > 11 \quad (3)$$

where

E_t = total evaporation in thousands of acre feet for month t,

e_t = the evaporation rate per unit of surface area for month t,

L_t = as defined in equation 2, and the coefficients for L were determined by least squares techniques using data from [27] and relate reservoir level in acre feet to surface area in acres.

The next step is to relate the amount of water in the reservoir from month to month thereby determining the amount of shortages and overflows if any. The basic relationship is

$$L_t = L_{t-1} - E_t + i_t - D_t \quad (4)$$

where

L_t = as defined in equation 2,

D_t = as defined in equation 1,

i_t = the inflow into the reservoir in thousands of acre feet for month t , and

E_t = as defined in equation 3.

If $L_t > R$ there is an overflow and L_t is made equal to R . If $L_t < 0$ the shortage in the delivery of irrigation water is

$$S_t = -2/3 L_t \quad (5)$$

where

S_t = the shortage in the amount of irrigation water delivered to the irrigation district in thousands of acre feet for the month t ,

$2/3$ = the inverse of the conveyance loss factor, and

L_t = as defined in equation 2.

After the shortage for the month, if any, is determined, L_t is redefined to be zero; that is, the reservoir is empty.

The process represented in the first five equations is repeated for all 468 months. At the end of each 12th month, however, the annual total amounts of rainfall (r_y) and delivery shortages (S_y) are obtained by summing the previous 12 monthly values. After

the yearly rainfall and shortage totals have been computed for each of the 39 years, the total annual water target for the irrigation district can be computed as

$$U = I T \quad (6)$$

where

U = total annual water target for the irrigation district in thousands of acre feet.

I = as defined in equation 1, and

T = as defined in equation 1.

In the next step the amount of irrigation water delivered to each farm must be obtained as

$$V_y = 16.67 (U - S_y - r_y I) \quad (7)$$

where

V_y = the amount of irrigation water delivered to each farm in acre feet for year y

16.67 = a factor (1,000/60) which accounts for the 60 farms in the district and the fact that U is in units of 1,000 acre feet, and all other variables are as defined previously.

The planned acres irrigated per farm is then

$$A = 333.3 (1/20) \quad (8)$$

where

A = the acres per farm that the system will try to furnish with the target amount of water T .

Next, the total annual water available for each enterprise can be determined by first subtracting the average annual rainfall from the

target and dividing this difference by the normal irrigation water requirement as, for example, those enterprises requiring eight inches of supplemental irrigation water per year would have the total water available calculated as

$$W_{8y} = V_y/A \left\{ \left[T - \left(\sum_{y=1}^{39} r_y / 39 \right) \right] / .67 \right\} + r_y \quad (9)$$

where

W_{8y} = the total water available in acre feet, to each farm for crops requiring eight acre inches of irrigation water per year in addition to the normal rainfall for year y .

Similar equations can be developed for the enterprises using 12, 16, 20 and 24 acre inches of irrigation water. Of course, for the dryland enterprises, the total water available (W_{0y}) is simply the natural rainfall (r_y).

The next step in this model involves the computation of the annual net returns from each of the 12 enterprises. For example, the net returns for the dryland cotton enterprise can be obtained from the following equation:

$$N_y = -54.83 + 52.44 W_{0y} \quad (10)$$

where

N_y = net returns per acre in dollars, for the dryland cotton enterprise.

Similar functions can be developed for the other 11 enterprises.

The process represented by equation 6 through 10 is repeated for each of the 39 years and produces per acre returns to each

enterprise for each year. The next step involves the computing of means, variances and covariances for each of the 12 enterprises

as

$$\bar{N}_c = \frac{\sum_{y=1}^{39} N_{yc}}{39} \quad (11)$$

and

$$s_{cc'} = \frac{\sum_{y=1}^{39} (N_{yc} - \bar{N}_c)(N_{yc'} - \bar{N}_{c'})}{38} \quad (12)$$

where

\bar{N}_c = the average annual net returns per acre over the 39 years for the particular enterprise c ,

$s_{cc'}$ = the variance, or covariance, of the average annual net returns of the enterprises c and c' , and

Σ = the matrix of elements $s_{cc'}$ for all combinations of c and c' ; that is, the variance - covariance matrix of average net returns for the 12 enterprises over the 39-year period.

The Farmer's Decision Process

After the means, variances and covariances of the net returns of the enterprises have been obtained, the optimal enterprise mix, and associated net returns from the whole farm and the marginal value product of water can be obtained using a technique suggested by Freund [8]. This technique involves maximizing the quadratic equation

$$P = \bar{N}'X - \alpha X' \Sigma X \quad (13)$$

subject to

$$BX \leq M$$

and

$$X \geq 0$$

where

P = the optimal net returns to the farm,

\bar{N} = a (column) vector of average annual net revenues per acre
for the 12 enterprises available to the farm,

X = a vector of the number of acres of each enterprise in a
productive program,

B = a matrix of the amounts of certain scarce resources;
land, allotments and water; needed by each acre of the
enterprise,

Σ = a matrix of the variances and covariances of the N_c ,

M = a vector of the available amounts of the scarce resources,
and

α = a scalar representing the degree to which the farmers
wish to avoid risk.

The solution provides the acreages of the enterprises and the net returns to the farm. The dual solution of the quadratic program also provides the marginal value product of irrigation water.

If this were a traditional linear programming problem, or if α were zero, then equation 13 would be reduced to $P = \bar{N}'X$.

In this problem, however, the amount of variance and covariance of the net returns of the enterprises, together with the farmer's desire to avoid variations in income are considered through the term $\alpha X' \Sigma X$. Thus, this procedure allows the farmers to trade off

income, for risk. The rate at which income is traded for less risk is determined by the strength of the farmer's desire to avoid risk which is represented by the size of the coefficient α .

Total Project Evaluation

The rest of the simulation model is designed to compute the primary net benefits, and/or the marginal value product net returns, which are used as an indication of the economic efficiency of the system. The primary benefits are obtained by multiplying the total returns to the farm by the number of farms in the irrigation district (60) and then subtracting the net returns to the district that could be obtained if no irrigation water were available. Then, from this remainder are subtracted the discounted annual repayment costs of the reservoir and irrigation development construction capital and the annual operation and maintenance costs. This final difference is the average annual primary net benefits that society would realize from the construction and operation of the system at a particular level of the design variables T, I and R. It should be noted that, contrary to common practice, secondary benefits are not accounted for in this study. They are omitted because they would contribute nothing to the purpose of developing a method for introducing risk to a simulation model. That is, the secondary benefits are simply a linear function of the primary benefits and thus would not change the relationship of one solution point to another in terms of economic efficiency.

The marginal value product returns are obtained by multiplying the marginal value product of the irrigation water by the annual average amount of irrigation water delivered to the irrigation district. The average annual delivery of irrigation water is obtained by determining the average (\bar{V}) farm delivery from equation 7. By subtracting the annual repayment costs of construction capital and the annual operation and maintenance costs from these returns, the average annual marginal value product net returns to the system can be obtained for the particular levels of the design variables T, I and R considered.

It should be noted at this point, that the entire model yields results for only one combination of levels of the design variables. Therefore each time that one or more of the levels of the design variables is changed, the entire procedure is repeated to obtain net benefits, or marginal value product net returns.

It is necessary, however, that the system be simulated using a wide range of levels of all of the design variables in order to obtain net benefits, or marginal value product net returns, over a wide range of combinations of levels. This is to facilitate the selection of an optimal combination of levels and to give an indication of how critical the loss of net benefits, or marginal value product net returns, might be if the optimal combination is not obtained. Thus, six reservoir capacities are considered ranging from a maximum of 300,000 acre feet down to zero in steps of 60,000 acre feet. Eight planned levels of development are used starting at a maximum of 20,000 acres and ranging down to 6,000

acres in steps of 2,000. Finally, seven levels of total annual water targets are considered ranging from a maximum of 5.67 acre feet per acre per year down to 3.67 acre feet per acre per year in steps of 3.33 acre feet. Thus a total of 336 separate combinations of levels of the three design variables are considered.

Operation of the Simulation Model

Basic Assumptions and Constraints Governing the Model

In addition to the constraints and assumptions discussed earlier concerning the basic properties of the system there are several important assumptions inherent in this model which warrant explicit discussion. One of these regards the assumption of the basic system used in this study. That is, it is assumed that the system consists of a reservoir for which the sole purpose is to provide water to an irrigation development. Such systems are rarely found in the real world, for most are designed to serve multiple purposes. While this assumption is made for the purpose of simplifying the task of developing methodological procedures one should note that it also restricts the amount of benefits that would normally be associated with such a project. Had other benefits, such as those from flood protection, recreation and municipal and industrial water supply, been included, their effects could have altered the optimal combination of levels of the design variables obtained.

This model also assumes that government programs, prices and farm production technology will remain constant over the life of the project. The project life is assumed to be 50 years as is standard in almost all water resource planning studies. The consequences of these assumptions of constant prices, programs and technology can hardly be determined with accuracy. However, if events of the past 50 years are any indication of what is to happen in the next 50, one may be sure that the assumptions are unrealistic.

Although the model allows for variations in the incomes of the farmers in the irrigation development due to variations in the amount of water available for crop production, it is assumed that the farmers know the nature of the variations that they face. That is, the model allows only for risk, not uncertainty. This means that for each level of the design variables considered, the farmers in the district can relate these levels of the design variables to a particular set of average net returns, including variances and covariances, for each of the 12 possible enterprises. This assumption, although somewhat unrealistic, is not inconsistent with the idea that the farmers should be able to obtain some knowledge of the risks associated with their water supply as affected by a particular combination of known levels of the design variables.

Another way in which the model deviates somewhat from reality is through the assumed operating procedure of the system. That is, the operators of the system are assumed to deliver all of the water

demanded by the crops at any particular time with no regard for the possibility of incurring shortages in the future. More realistic operational procedures allow for partial deliveries of water when the reservoir level becomes low in order to insure against the total loss of a crop later in the season due to a lack of water. While this assumption might seem quite limiting it is not of serious consequences in this study because of another, even more limiting, assumption. That is, this model assumes that the four crops, or 12 enterprises, respond to total annual water regardless of when it becomes available within the year. Even though the water demanded by the crops is broken down into monthly periods, the functions which relate the available water to net returns from the enterprises are based on annual time periods. This assumption is necessary due to the limited amount of data available regarding the response of crops to water and particularly the effects of the timeliness of water availability. Enough is known, however, to state that the consequences of such an assumption can be quite significant. For example, three acre feet of water per year, when it is optimally available to the crops during the growing season, certainly does not produce the same yield as when only one acre foot is available to the crops during the growing season and the other two acre feet of water are available at other times during the year.

Several other assumptions are made in the model and should be noted. One which is slightly less limiting than those previously

discussed, regards the manner in which water must be applied to a set of enterprises. It is assumed that once the enterprise mix for a farm has been selected, it is inflexible and each enterprise in the mix gets its proportional share of any and all water available regardless of how little or how much it might be. This means that if a water shortage occurs, the farmers cannot abandon one enterprise and use all of the available water on another. This assumption deviates from common practice, but is necessary to facilitate the operational determination of the optimal enterprise mix.

Somewhat related to the previous assumption is another which does not allow for more supplemental irrigation water to be made available per year to any enterprise than the enterprise normally requires. For example, if an enterprise normally requires eight acre inches of irrigation water in addition to the normal rainfall, then the model allows no more than eight acre inches per acre of irrigation water to be applied to it. This assumption is necessary in order to facilitate the operational determination of the proper net returns from the enterprises.

Finally, an assumption which is evident in the model, but also rather important, is the one regarding the allocation of the available irrigation water among the enterprises. That is, the allocation of the available water is determined by the water requirements of the enterprises and the farmer's most profitable combinations of enterprises and without regard to the planners' target level (T) or planned acres irrigated (I). Thus, the levels of the design

variables T and I do not directly restrict the actual level of irrigation water application or the number of acres irrigated. The levels of the design variables do, however, affect the actual distribution and allocation of irrigation water through their affect on the amount of water provided to the farms.

Capabilities of the Model

For each combination of levels of the design variables reservoir capacity (R), total available water target (T) and acres planned for irrigation (I), the simulation model determines an annual total amount of water available to each of the 12 enterprises. This is accomplished for each of the 39 years for which the hydrologic data are available. Using these annual total amounts of water available, annual net returns for each of the enterprises for each of the 39 years can be determined through the functions represented by equation 10. Thus, a mean, variance and covariance for the net returns over the 39-year period can be determined for each level of R , T , and I .

These means, variances and covariances of the net returns are then used in a procedure developed by Freund [8] which incorporates into a standard programming optimization a device whereby a farmer can trade off income for risk at a rate which is determined by his particular desire to avoid risk. That is, Freund's procedure allows a farmer to select an optimal combination of enterprises for his farm which will maximize his income, subject to the constraint that he can choose to give up some income in order to avoid risk

in the form of variations in income. The rate at which he might choose to trade off income for risk, is of course dependent on many circumstances. These circumstances include the farmer's capital position, the size of the risk, or amount of income variation that he must deal with and his psychological make-up. This characteristic of the model makes it adaptable to a wide range of income-risk situations which could not heretofore be accounted for in a water resource system planning model.

Freund [8] represented the farmers' desire to avoid risk by a "risk aversion constant" (α) (see equation 13). Since Freund did not, however, provide any guides for determining α , the level of α used in this study was determined by a trial and error process. That is, starting with the assumption that no irrigation water was available and with an α level of zero (no risk aversion), successively larger levels of α were tried. Eventually, one was found which would cause the farmers to give up income to the point that they would not utilize all of their available farm land in order to avoid risk. The α level thus obtained (0.00006) was judged to be one level above what could be assumed as a realistic upper limit for the level of α since it was known that the farmers in the area did actually utilize all of their available farm land, even in a dryland situation. Thus, the α level of 0.00005 was used in this study as the level most representative of the farmers' desires to avoid risk.

The actual solution of the problem of finding an optimal set of enterprises requires the solution of a quadratic programming problem (see equation 13). Since the function to be maximized is concave to the origin it is possible to use an algorithm developed by Hartley and Hocking [11] and programmed by LaMotte and Oxspring [17]. This algorithm is incorporated into the simulation model as a subroutine. Thus, Freund's procedure [8] is used as a proxy for the decision making process of the farmers whose objectives are to maximize income while allowing them to trade income for risk, or income variance. Of course, they can also utilize only the amounts of land, allotments and water which are available to them.

The results obtained from this step in the simulation model include the optimum combination of enterprises for the farms and the solution value of the optimized function (see equation 13). It should be pointed out here that the solution value of the optimized function, as obtained from the solution of the quadratic program, is not in terms of actual dollars, unless the value of α used is zero. That is, the optimal solution of the equation $\bar{N}'X - \alpha X' \Sigma X$ would be given as a value that would be less than actual dollars by the amount of $\alpha X' \Sigma X$. Of course, the solution value would be in terms of actual dollars if α were equal to zero. These solution values, for solutions where α is greater than zero, are termed risk free dollars, because they represented the amount of risk free income that the farmer would be willing to have rather than the amount of variable, or risky, income that he would

actually receive. However, this does not represent a serious limitation in this study because the program makes available the optimal levels of each of the enterprises in the final solution. These levels can be multiplied by their respective average annual net returns and the sum of these products acquired to obtain the optimum actual income for the farms.

Similarly, the marginal value products from the dual solution of the quadratic program, are given in risk free dollars. These marginal value products represent the value to the farm of an additional unit of whatever resource is limiting at the final solution point.²

However, since they are in terms of risk free dollars their value is known to differ by some small, but indiscernible, amount from the marginal value products in actual dollars.

The exact amount of the difference between the actual and risk free marginal value products depends on the size of the risk aversion constant and the amount of variance and covariance present in the combination of enterprises in the optimum solution. As far as the author can ascertain, this difference can be either positive, or negative, and is usually no more than ten percent of the marginal value products when an α value of 0.00005 is used.

²For a detailed explanation of the correct interpretation of the dual solution in nonlinear programming see [3].

This situation represents a limitation to the proposed marginal value product approach since the marginal value product of water and the returns to the system from the sale of water priced at its marginal value product would necessarily be in terms of risk free dollars. This situation is, however, unavoidable.

CHAPTER III

Basic Data Inputs to the Model

Cost Data for the System

The water resource system considered in this study is basically the same system simulated by Bathke [5] and is located on the South Concho River near the Texas city of San Angelo. Total construction costs of the reservoir are estimated by the two part function:

$$TCR = 9.9392 + 0.1047R - 0.0004R^2, R \leq 134, \text{ and} \quad (14)$$

$$TCR = 13.4823 + 0.329R, R > 134,$$

where

TCR = total construction costs of the reservoir in thousands of dollars, and

R = capacity of the reservoir in thousands of acre feet.

Equation 14 represents a slight modification of Bathke's original function in that the last part of the two part equation had to be added to accommodate the larger reservoir sizes required in this study. These equations were, however, based on costs data provided by Bathke.

Total construction costs of the irrigation development are

$$TCI = 1.1788 + 0.0997I - 0.0004I^2 \quad (15)$$

where

TCI = total construction costs of the irrigation development in thousands of dollars, and

I = the actual irrigated acres in the irrigation development
in thousands of acres.

The total construction costs of the reservoir and irrigation development had to be put on an annual repayment basis in order to obtain annual benefits. Again, the coefficient by which the total costs were multiplied in order to obtain the annual repayment was taken from Bathke [5] and is

$$RC = d / (1 - (1+d)^{-n}) \quad (16)$$

where

RC = repayment coefficient,

d = interest rate in percent (set at 0.03) and

n = number of years allowed for repayment (set at 50).

The annual operation and maintenance costs given by Bathke [5] were modified, again using data provided by him, in order to incorporate both the reservoir and irrigation development into its formulation. Thus, annual operation and maintenance costs in thousands of dollars are

$$OMC = 51.8330 + 0.4I + 0.11R \quad (17)$$

where I and R are described in the previous equations.

Thus, the total annual costs for the system can be obtained as

$$\text{Total annual costs} = RC \cdot TCR + RC \cdot TCI + OMC \quad (18)$$

where all of the variables are as defined in the previous equations.

These total annual costs can be subtracted from the annual benefits to obtain the total net benefits to society from the system.

The Hydrologic Data

The historical hydrologic data concerning stream flows, evaporation rates and rainfall, shown in Appendix A, came from the Corps of Engineers Report on the San Angelo Project [27]. These data were compiled prior to the construction of the Twin Buttes Reservoir on the South Concho River in the late 1950's. The data includes the effective monthly rainfall, or rainfall minus allowances for runoff and deep percolation losses. The rainfall data were recorded at San Angelo, Texas from January, 1916 through December, 1954. Also included are monthly evaporation rates per unit of surface area, and the monthly stream flow rates for the South Concho River for the same period. The most striking characteristic of these data is the wide variation both between years and between months within years. These variations make these data well suited to the purpose of this study because of the large amount of risk inherent in a water resource system which is subject to such conditions.

Thirty-nine years is not usually considered a sufficient period of time over which to evaluate the simulated effects of design variables in studies such as this one. These 39 years of data could be used to establish a probability distribution, from which longer data periods could be generated. Such procedures would not, however, aid in the development of the methodological procedures and are thus omitted.

Crop Production, Costs and Returns Data

The data concerning crop production costs and returns and the effects of different amounts of water on crop yields were taken from several sources [14, 15, 18, 20, 22, 23 and 26]. As was explained earlier, each of the 60 farms in the irrigation development can choose between four basic crops which are further broken down into 12 production enterprises. The crops, cotton, grain sorghum, oats and alfalfa are representative of the types of crops that would be produced in the area under the wide range of irrigation water availabilities that are considered.

All of the relevant production costs and returns for the various enterprises are included in Tables 1 through 4 with the exception of the basic labor expenses of the farm operator and the costs of the irrigation water. The operator's labor is excluded because it is basic to all of the enterprises, and the income from operating the farm is assumed to be payment for the operator's labor. The additional amounts of labor required for applying irrigation water are, however, charged against the enterprises which use irrigation water. The costs of the irrigation water is not charged against the enterprises because the farm income, over and above the income which would accrue to the farms if no irrigation water were available, is used to determine the benefits from the system. Thus, the costs for the water are charged against the system so that the proper net benefits can be obtained.

Table 1 shows the representative costs and returns associated with the production of cotton. There are four basic cotton producing enterprises. The first, entitled "Dryland Cotton," does not receive any water other than natural rainfall. It is included because it could be profitably used in an optimal enterprise mix for the farms if a small amount of irrigation water were available, or in conjunction with other heavily irrigated enterprises.

The enterprise from Table 1 entitled "Cotton Irrigated Once" requires, on the average, one eight-inch application of supplemental irrigation water per acre. This irrigation water together with the 19 inches of normal (average) rainfall per year means that this enterprise normally requires about 27 acre inches of water per year.

The enterprise entitled "Cotton Irrigated Twice," from Table 1 receives, in addition to the eight acre inches given the once-irrigated enterprise, another application of four inches of irrigation water per acre. Similarly, the enterprise shown in Table 1 entitled "Cotton Irrigated Three Times," gets a total of 16 inches of irrigation water per acre in addition to the normal 19 acre inches of rainfall. This latter practice is rarely found in the area but is included because it would be expected to become profitable if large amounts of irrigation water were available.

Table 2 shows the representative costs and returns associated with the production of grain sorghum. The five grain sorghum

Table 1.--Representative cotton production costs and returns, Tom Green County, Texas, 1967^a

Item	Enterprises			
	Dryland Cotton	Cotton Irrigated- One Time	Cotton Irrigated- Two Times	Cotton Irrigated- Three Times
Production Costs Per Acre:				
Seed	\$ 1.92	\$ 1.92	\$ 2.40	\$ 2.80
Tractor and equipment	3.55	3.55	3.95	4.35
Fertilizer (nitrogen)	1.80	1.80	7.20	9.60
(phosphorus)	1.35	1.35	3.60	5.40
Insecticide	2.00	2.00	18.00	30.00
Herbicide	2.00	2.00	5.40	5.40
Labor due to irrigation	--	3.00	4.20	6.50
Defoliants	2.00	2.00	--	--
Interest on operating capital	.44	.55	1.57	2.24
Total Production Costs/Ac.	15.60	18.17	46.32	66.29
Expected Net Returns/Ac. ^b	32.57	64.53	69.85	97.65
Harvesting Costs:				
Stripping; \$0.75/cwt. of seed cotton (1 bale = 1,900 lbs. of Seed Cotton)				
Hauling; \$0.25/cwt. of Seed Cotton				
Bagging and ties; \$5.75/bale				
Ginning; \$0.75/cwt. of Seed Cotton				
Total Harvesting Costs = \$7.78/cwt. of lint				
Returns:				
Lint Cotton; \$0.28/lb. ^c				
Cotton Seed; \$3.35/cwt. (1.65 lbs. of seed per lb. of lint)				

^aThe data in this table were derived primarily from USDA sources [22, 26]. Modifications, however, were made in updating costs and prices and in fitting the production practices to the Tom Green County area. These modifications were based largely on discussions with local county agricultural officials, other professional agricultural workers familiar with farming practices in the area and other sources [14, 20].

^bExpected net returns are the difference between production costs and returns from the sale of the crop assuming a normal yield.

^cIncludes Government price supports and compliance with a minimal diversion requirement of 1/3 of the base allotment.

Table 2.--Representative grain sorghum production costs and returns, Tom Green County, Texas, 1967^a

Item	Enterprises							
	Dryland Grain Sorghum	Grain Sorghum Irrigated One Time	Grain Sorghum Irrigated Two Times	Grain Sorghum Irrigated Three Times	Grain Sorghum Irrigated Four Times			
Production Cost Per Acre:								
Seed	.75	.75	1.50	2.25	2.25			
Tractor and equipment	3.00	3.00	3.77	4.69	5.28			
Fertilizer (nitrogen)	1.80	1.80	3.60	5.40	7.20			
(phosphorus)	1.35	1.35	1.80	2.70	3.60			
Fertilizer application			.15	.15	.15			
Herbicide			5.60	5.60	5.60			
Additional labor for irrigating		3.00	4.90	6.30	7.35			
Harvesting (combining)	3.00	3.00	3.00	3.00	3.00			
Interest on operating capital	.24	.34	.75	.95	1.10			
Total Production								
Cost Per Acre:	10.14	13.24	25.07	31.04	35.53			
Expected Net Returns/Ac.: ^b	11.91	27.08	36.69	46.37	59.20			
Returns:								
Grain Sorghum:	\$1.75/cwt. (-\$0.10/cwt. hauling = \$1.65/cwt.)							

^aThe data in this table were derived primarily from USDA sources [22, 26]. Modifications, however, were made in updating costs and prices and in fitting the production practices to the Tom Green County area. These modifications were based largely on discussions with local county agricultural officials, other professional agricultural workers familiar with farming practices in the area and other sources [14, 20].

^bExpected net returns are the difference between production costs and returns from the sale of the crop assuming a normal yield.

production enterprises shown include the widest possible range of production practices applicable to the crop. The first four enterprises, "Dryland Grain Sorghum," "Grain Sorghum Irrigated Once," ". . . Twice" and ". . . Three Times" receive the same amounts of water as the similarly titled cotton enterprises from Table 1. The enterprise entitled "Grain Sorghum Irrigated Four Times" normally receives 20 acre inches of irrigation water per year in addition to the natural rainfall. In a like manner, Tables 3 and 4 show costs and returns for irrigated alfalfa and dryland and irrigated oats respectively. Budgets for dryland alfalfa were not included because alfalfa cannot be profitably produced in the area without supplemental water. Normal water requirements for "Irrigated Alfalfa" include 24 acre inches of irrigation water per year in addition to normal rainfall. "Irrigated Oats" normally receive 16 acre inches of irrigation water per year while "Dryland Oats" receive only the normal rainfall.

Although each of the 12 enterprises discussed has associated with it normal water requirements, yields when the amount of water available is not normal are also of concern. Therefore, functions representing the yield response to different amounts of total annual water per acre for each of the 12 enterprises were obtained and are shown in Table 5. These data were derived from several sources regarding plants response to water [14, 15, 18, 22 and 23].

Table 3.--Representative alfalfa production costs and returns, Tom Green County, Texas, 1967^a

Item	Irrigated Alfalfa Cost/Ac.
Production Costs Per Acre:	
Seed	7.50
Tractor and equipment	5.80
Fertilizer (nitrogen)	1.80
(phosphorus)	9.00
(potassium)	.90
Insecticide	4.00
Fertilizer application	.30
Labor	9.80
Interest on operating capital	<u>1.37</u>
Total Production Cost Per Acre	40.47
Returns:	
Alfalfa forage; \$25.00/ton	
Harvesting cost; \$-4.85/ton	
Returns; \$21.15/ton	
Expected Net Returns Per/Ac.; ^b	60.08

^aThe data in this table were derived primarily from USDA sources [22, 26]. Modifications, however, were made in updating costs and prices and in fitting the production practices to the Tom Green County area. These modifications were based largely on discussions with local county agricultural officials, other professional agricultural workers familiar with farming practices in the area and other sources [14, 20].

^bExpected net returns are the difference between production costs and returns from the sale of the crop assuming a normal yield.

Table 4.--Representative oat production costs and returns, Tom Green County, Texas, 1967^a

Item	Dryland Oats	Irrigated Oats
Production Costs Per Acre:		
Seed	2.25	3.00
Tractor and equipment	1.88	3.20
Fertilizer (nitrogen)	1.80	7.20
(phosphorus)	.90	3.60
Insecticide	--	1.60
Fertilizer application	--	.15
Additional labor for irrigation	--	4.90
Interest on operating capital	.24	.83
Harvesting (combining)	<u>3.00</u>	<u>3.00</u>
Total Production Costs Per Acre	10.07	27.48
Returns:		
Grain; \$0.70/bu.		
Grain hauling; \$0.07/bu.		
Returns from grain; \$0.63/bu.		
Returns from forage grazing; \$3.00/animal unit month		
Expected Net Returns/Ac.: ^b	4.59	39.07

^aThe data in this table were derived primarily from USDA sources [22, 26]. Modifications, however, were made in updating costs and prices and in fitting the production practices to the Tom Green County area. These modifications were based largely on discussions with local county agricultural officials, other professional workers familiar with farming practices in the area and other sources [14, 20].

^bExpected net returns are the difference between production costs and returns from the sale of the crop assuming a normal yield.

Table 5.--Representative crop yield responses to varying levels of total water available per year

Water/Yr. (Ac. Ft.)	CROPS									
	Cotton Lint					Oats				
	Dryland (lbs.)	Irrigated Once (lbs.)	Irrigated Twice (lbs.)	Irrigated Three Times (lbs.)	Grain (bu.)	Grazing (A.U.M.)	Grain (bu.)	Grazing (A.U.M.)	Irrigated Grain (bu.)	Irrigated Grazing (A.U.M.)
1.00	33	33	10	0	0	0	0	0	0	0
1.33	110	110	100	5	6	1.0	5	.5		
1.67	171	171	180	50	15	2.0	16	1.5		
2.00	242	242	275	190	24	2.5	32	2.5		
2.33	319	319	370	280	35	3.0	52	3.5		
2.67	341	341	450	420	42	3.5	69	4.5		
3.00	451	451	575	620	46	4.0	82	5.0		
3.33	517	517	650	750	48	4.0	90	5.0		
3.67	570	570	670	825	45	3.5	84	4.5		
4.00	500	500	600	750	38	2.5	70	3.5		

Table 5.--Continued

Water/Yr. (Ac. Ft.)	CROPS					
	Grain Sorghum			Alfalfa		
	Dryland (lbs.)	Irrigated Once (lbs.)	Irrigated Twice (lbs.)	Irrigated Three Times (lbs.)	Irrigated Four Times (lbs.)	Irrigated (Tons)
1.00	225	225	150	0	0	0
1.33	800	800	400	0	0	0
1.67	1270	1270	850	200	125	.5
2.00	1810	1810	1350	800	775	1.5
2.33	2440	2440	2475	2100	1900	2.4
2.67	3100	3100	3750	3500	3300	3.0
3.00	3610	3610	4250	4700	4700	3.7
3.33	4000	4000	4675	5600	5750	4.5
3.67	3700	3700	4700	5900	6350	5.0
4.00	3000	3000	4600	5700	6300	5.8

Information regarding the relationships represented in Table 5 was, however, very sketchy and in some instances non-existent as far as the author could ascertain. Therefore, it was necessary to supplement the available data with value judgments concerning realistic and plausible responses. Such decisions were to a great extent based on discussions with other agricultural scientists in order to insure the reasonableness of the response functions. Two facts concerning these data should be noted. First, the relationships concern the response of crops to total annual water available, and second, there exists a serious lack of data supporting such relationships. Thus, although the data are reasonable they certainly are no more than approximately accurate or correct. This shortcoming is not deemed too serious in this study, however, since the purpose here is to develop methodology.

From these water-crop yield relationships and the production costs and returns represented in Tables 1 through 4, functions representing the relationship between net returns per acre and total annual water per acre for each of the 12 enterprises were constructed. These functions can be seen graphically in Figures 2 through 4 and algebraically in Tables 6 through 8. Note, that the functions for the more intensively irrigated enterprises, while generally producing large net returns in response to large amounts of annual available water, produce rather severe losses (negative returns) when the total amount of water available is small.

Fig. 2.--Cotton net returns as a function of total annual water

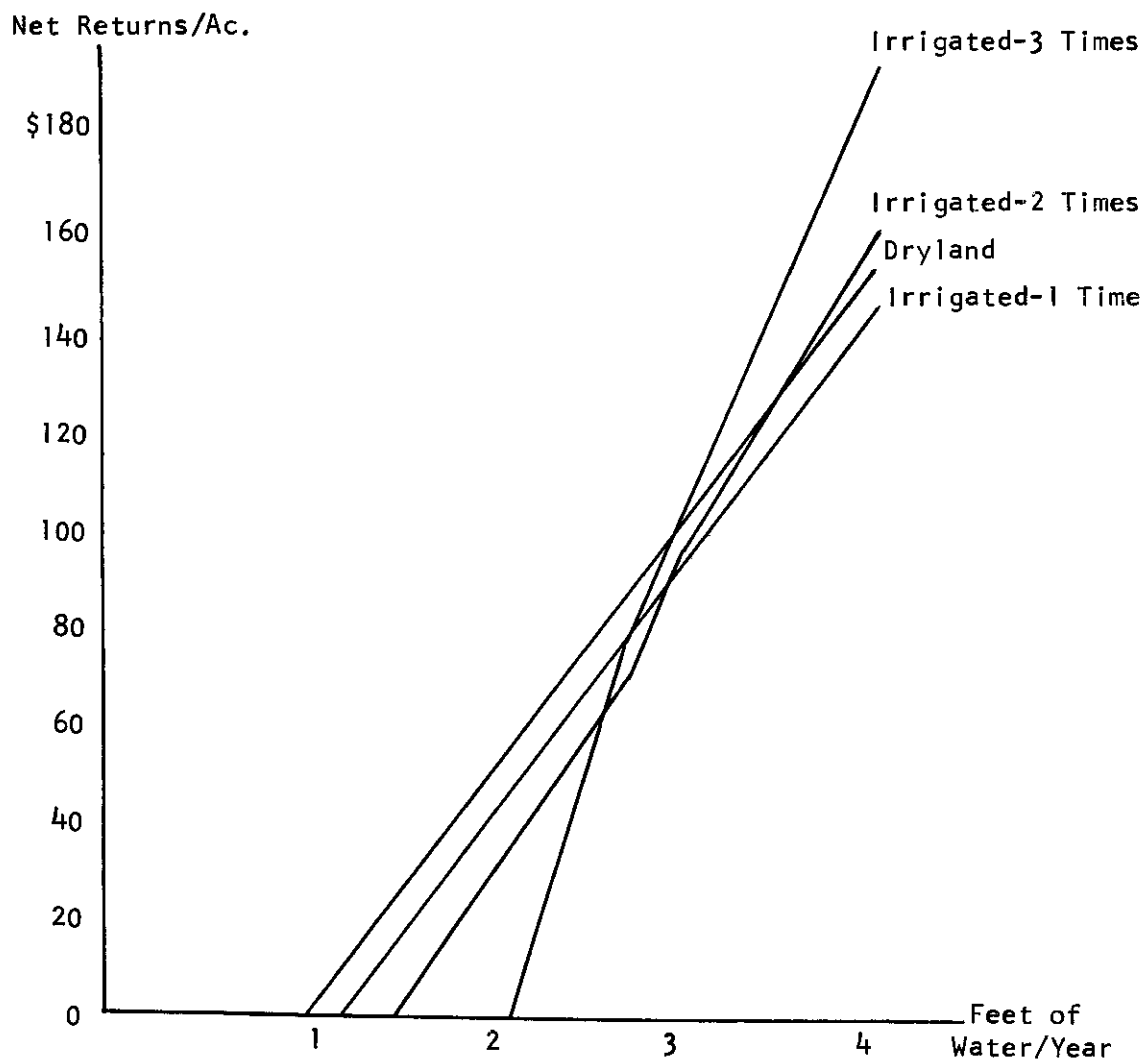


Fig. 3.--Grain sorghum net returns as a function of total annual water

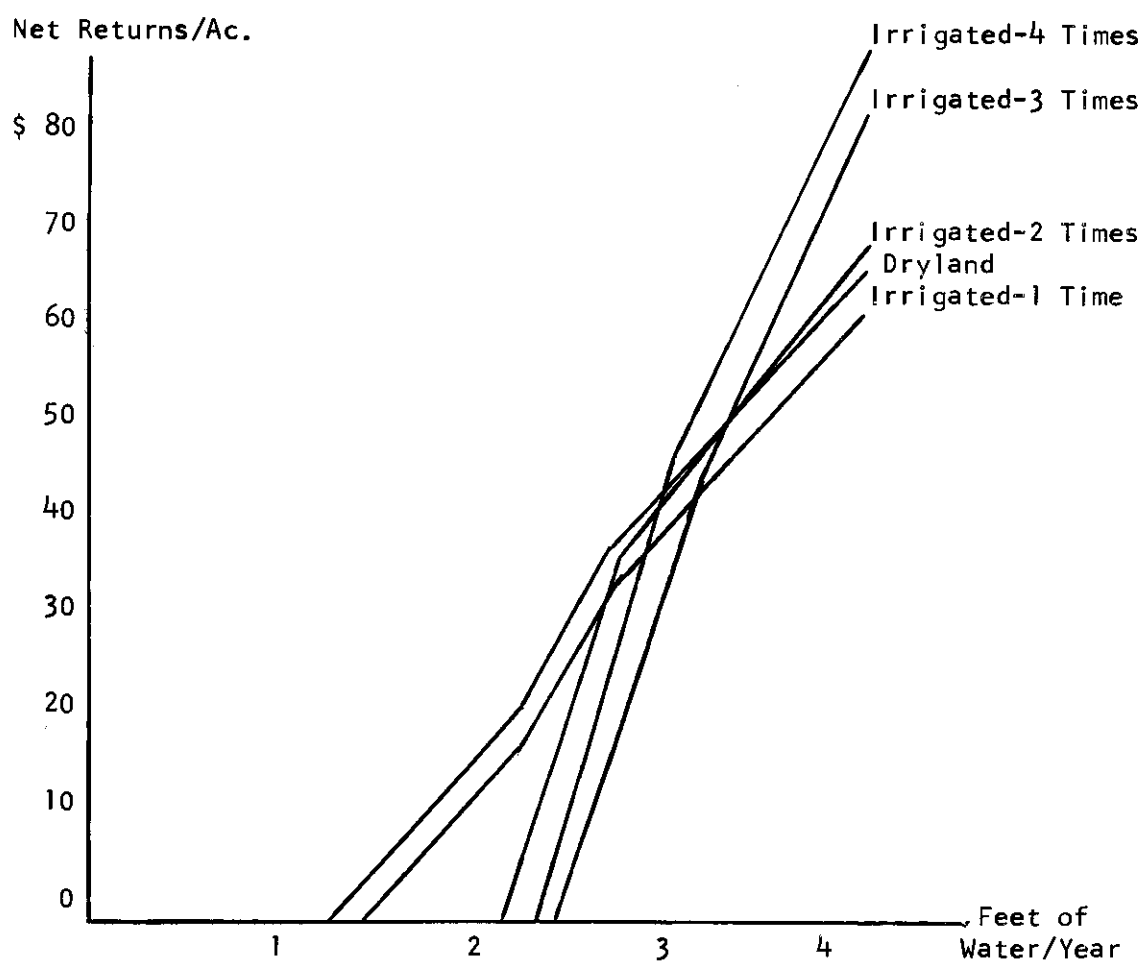


Fig. 4.--Oats and alfalfa net returns as a function of total annual water

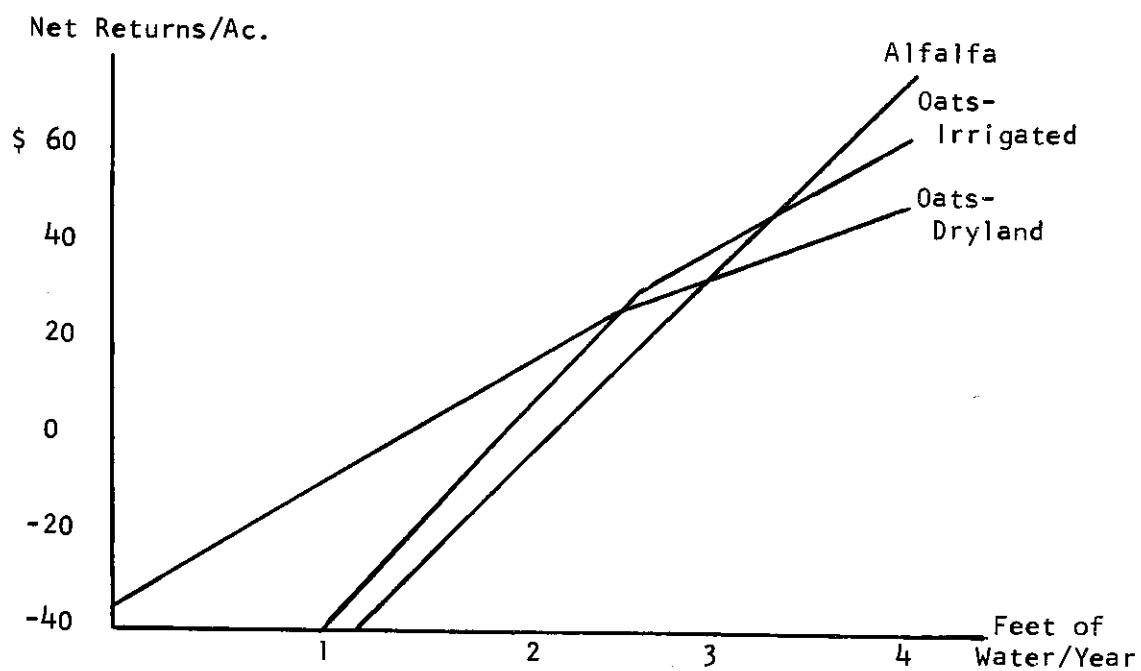


Table 6.--Cotton net returns (N) as a function of total annual water (W)

Dryland Cotton:

$$N = -54.83 + 52.44W$$

Cotton Irrigated Once:

$$N = -57.94 + 52.44W$$

Cotton Irrigated Twice:

$$\begin{aligned} N &= -88.28 + 59.16W, W \leq 2.67 \\ N &= -187.75 + 96.60W, 2.67 < W \leq 3.0 \\ N &= -72.18 + 58.08W, W > 3.0 \end{aligned}$$

Cotton Irrigated Three Times:

$$\begin{aligned} N &= -242.18 + 108.12W, W \leq 2.67 \\ N &= -349.02 + 148.56W, 2.67 < W \leq 3.0 \\ N &= -203.31 + 100.32W, W > 3.0 \end{aligned}$$

Table 7.--Grain sorghum net returns (N) as a function of total annual water (W)

Dryland Grain Sorghum:

$$\begin{aligned} N &= -31.54 + 25.92W, W < 2.17 \\ N &= -46.08 + 32.64W, 2.17 < W \leq 2.67 \\ N &= -18.56 + 22.32W, W > 2.67 \end{aligned}$$

Grain Sorghum Irrigated Once:

$$\begin{aligned} N &= -34.64 + 25.92W, W \leq 2.17 \\ N &= -49.18 + 32.64W, 2.17 < W \leq 2.67 \\ N &= -21.66 + 22.32W, W > 2.67 \end{aligned}$$

Grain Sorghum Irrigated Twice:

$$\begin{aligned} N &= -144.40 + 7.92W, W \leq 2.67 \\ N &= -29.22 + 24.72W, W > 2.67 \end{aligned}$$

Table 7.--Continued

Grain Sorghum Irrigated Three Times:

$$N = -146.69 + 64.32W, W \leq 3.0$$

$$N = -87.18 + 44.52W, W > 3.0$$

Grain Sorghum Irrigated Four Times:

$$N = -166.19 + 9.3W, W \leq 3.0$$

$$N = -114.00 + 51.9W, 3.0 < W \leq 3.33$$

$$N = -60.20 + 3.00W, W > 3.33$$

Table 8.--Oats and alfalfa net returns (N) as a function of total annual water (W)

Dryland Oats:

$$N = -34.28 + 23.40W, W \leq 2.5$$

$$N = -9.08 + 13.32W, W > 2.5$$

Irrigated Oats:

$$N = -87.74 + 43.92W, W \leq 2.69$$

$$N = -48.05 + 29.04W, 2.67 < W \leq 3.0$$

$$N = -31.13 + 23.04W, W > 3.0$$

Irrigated Alfalfa:

$$N = -95.17 + 43.56W, W \leq 3.33$$

$$N = -50.79 + 30.24W, 3.33 < W \leq 3.67$$

$$N = -129.12 + 51.60W, W > 3.67$$

CHAPTER IV

Results of the Simulation

In this chapter, the results obtained from simulating the effects on the system of the different combinations of levels of the design variables are presented and discussed. Values of the net benefits, and marginal value product net returns, were obtained for every different combination of the levels of reservoir capacity (R) annual available water target (T) and planned irrigated acres (I). These different levels of net benefits, and marginal value product net returns, were fit, using least squares techniques, to a function relating the different combinations of levels of the design variables to the net benefits, or marginal value product returns. These functions, or response surfaces, could then be examined and evaluated and the optimal combination of levels of the design variables selected. An example of the results of the simulation and the type of data that was used to estimate the response surfaces is shown in Appendix B.

The discussion in this chapter will initially be concerned with solutions obtained from data sets simulated using a risk aversion constant of $\alpha = 0.00005$. This level was chosen, as discussed in Chapter II, because it appears that this level of α represents a realistic upperbound of the desires of the farmers to avoid risk.

The Primary Net Benefits Response Surface

The quadratic response surface of annual primary net benefits was fitted using least squares techniques. The surface can be represented in equation form as

$$B_{19} = -4682.1 + 1087.5T + 461.51I - 2199.4R - 64.7T^2 - 12.1I^2 - 5555.6R^2 - 56.8TI + 430.1TR + 202.6IR \quad (19)$$

where

B_{19} = annual primary net benefits to society in thousands of dollars,

T = the total amount of water, in feet, both irrigation and rainfall, that the system planners try to furnish each acre that they plan to irrigate,

I = the amount of land that the system planners try to furnish with T in thousands of acres, and

R = the capacity of the reservoir in millions of acre feet.

Although the absolute maximum value of B_{19} is not obtainable, because the matrix of first partial derivatives of equation (19) is not negative definite, a maximum within the area of interest is found where $T = 5.67$, $I = 7$ and $R = 0.150$. The area of interest is defined as an area for which the level of R is greater than zero but less than 0.300, the level of I is greater than zero but less than 20 and the level of T is greater than zero but less than 5.67. These locally optimum levels of R , I and T produce a B_{19} value of -89,000 dollars. One should note that the annual primary net benefit value is negative indicating that annual costs of the

system are larger than the expected annual primary benefits. If secondary benefits has been accounted for it is reasonable to assume that the total net benefit value would have been positive.

An interesting interaction between T and I is illustrated in Figure 5. As can be seen the difference in the level of B_{19} along the ridge line between the points $T = 5.67$, $I = 7$ and $T = 4$, $I = 11$ is only 28,000 dollars. This means that the planners of the system can make substitutions between target deliveries and planned levels of development with essentially no change in net benefits. This interaction is due primarily to the fact that delivery target and level of development are the two primary factors that the planners use in determining how much irrigation water they will try to supply to the district. The amount that is actually supplied is, of course, affected by these variables but is also influenced by the amount of rainfall and evaporation and the size of the reservoir.

Graphs depicting primary net benefits as a function of T and R , and I and R are shown in Figures 6 and 7 respectively. They reveal, as would be expected, that as the target deliveries and/or planned acres irrigated get larger, larger reservoirs are needed for maximum net benefits. The author, however, could see no other meaningful patterns in the figures. Of interest, however, are the relative sensitivities of the local maximum with respect to each of the three design variables. The sensitivities were obtained by taking the partial derivatives of equation 19 with respect to each of the three design variables, R , T and I and then multiplying each by the ratio

Fig. 5.--Annual primary net benefits (in \$1,000) as a function of delivery target (T) and planned acres irrigated (I) using a risk aversion constant of $\alpha = 0.00005$ and reservoir capacity of 150,000 Ac. Ft.

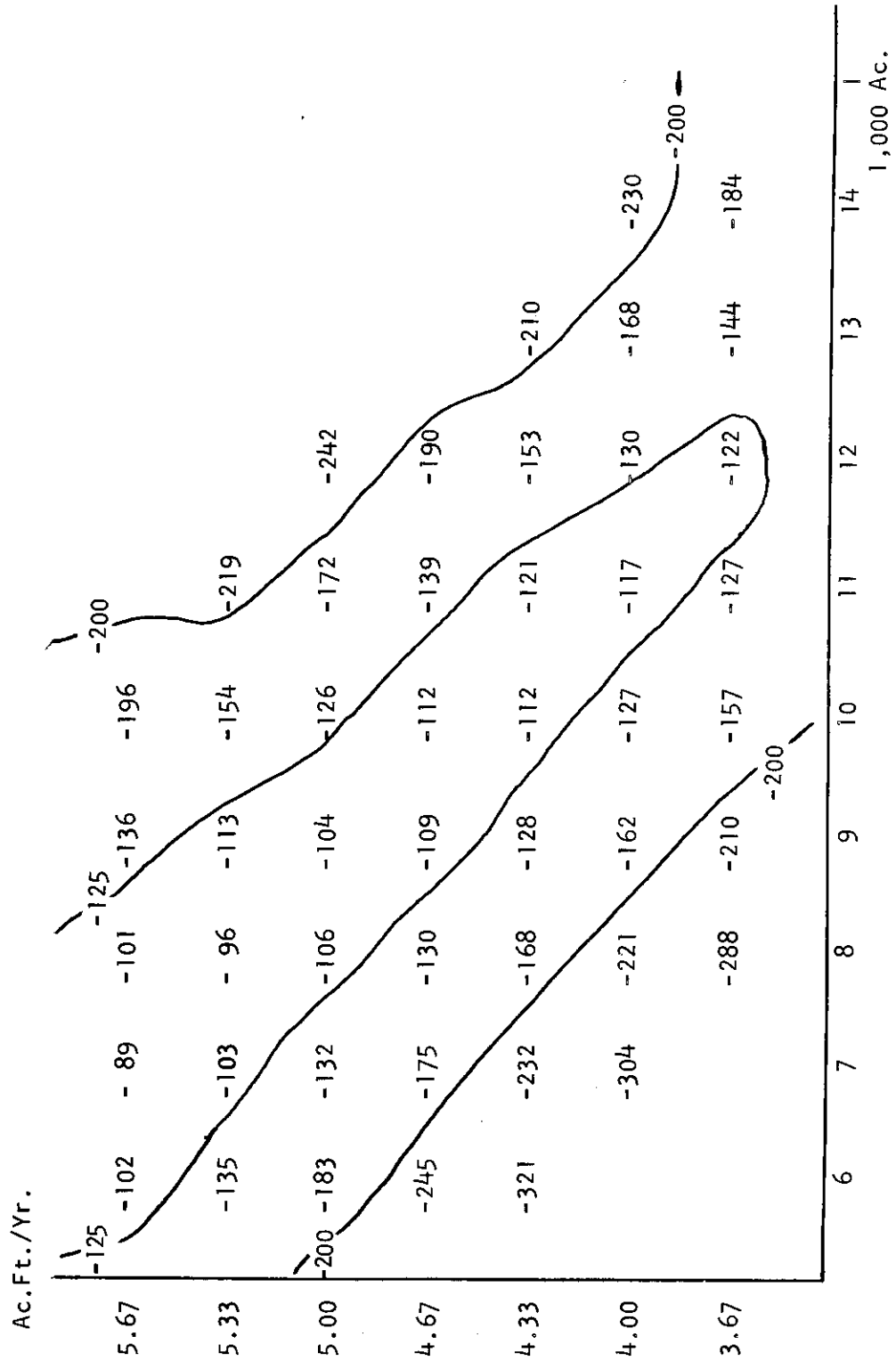


Fig. 6.--Annual primary net benefits (in \$1,000) as a function of reservoir capacity (R) and delivery target (T) using a risk aversion constant of $\alpha = 0.0005$ and planned acres irrigated = 6,000

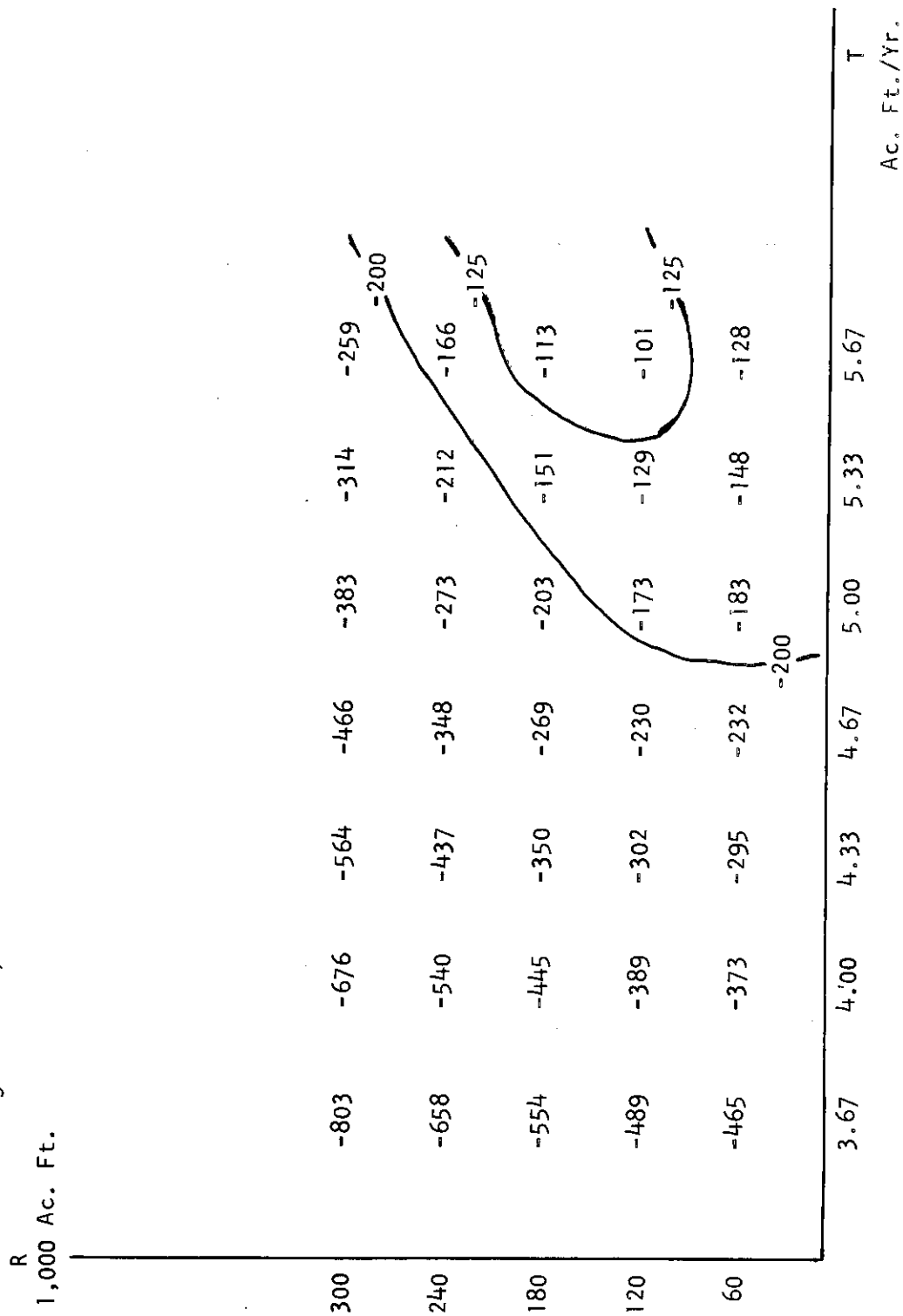
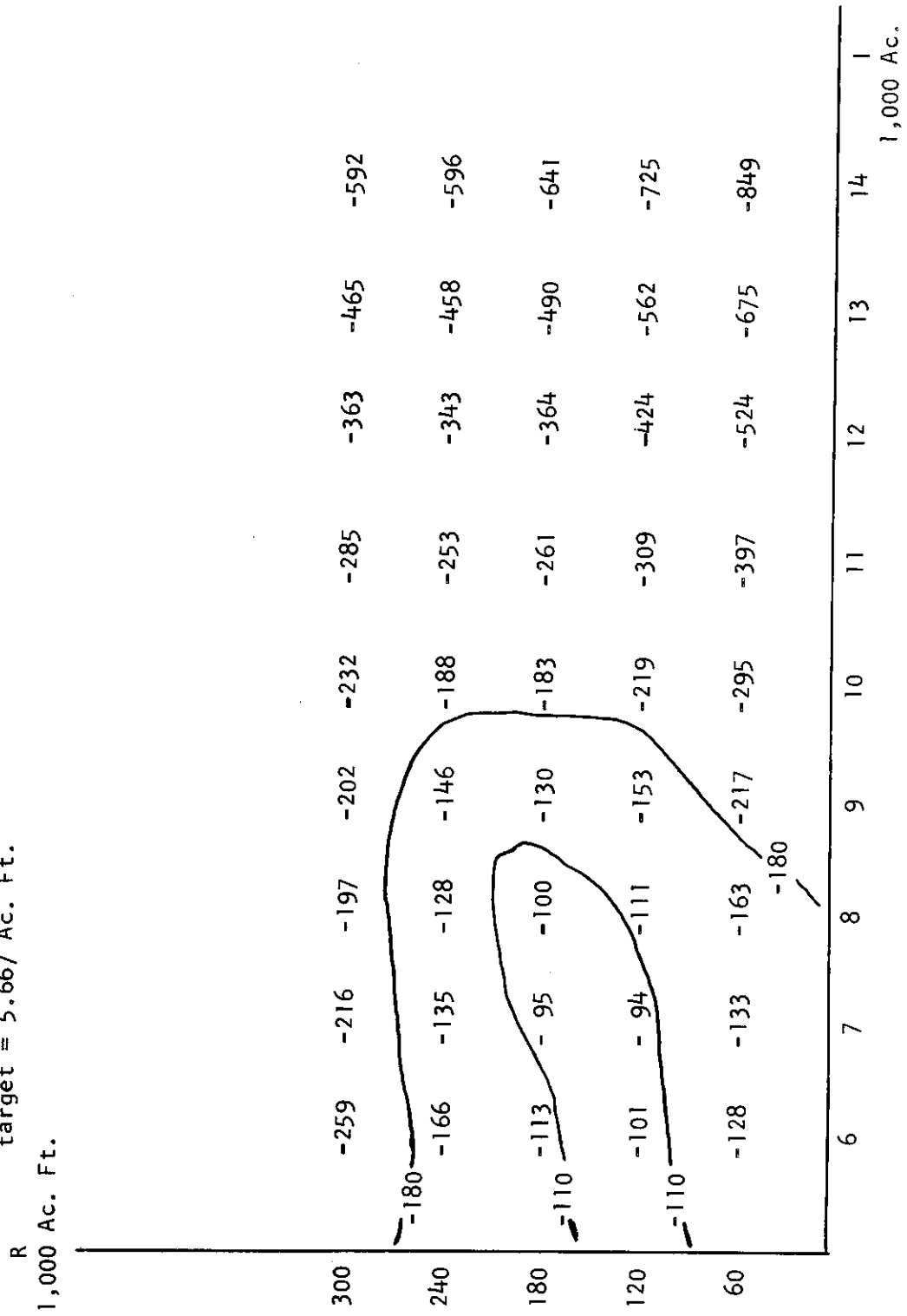


Fig. 7.--Annual primary net benefits (in \$1,000) as a function of reservoir capacity (R) and planned acres irrigated (I) using a risk aversion constant of $\alpha = 0.0005$ and a delivery target = 5.667 Ac. Ft.



of the decision variable to the annual primary net benefits at the local maximum. These sensitivities are 2.510 for T, 0.425 for I and 0.126 for R. This means that an increase or decrease of one percent in the level of T, from the optimal solution level, would produce a 2.510 percent increase or decrease in the primary net benefits. Likewise, an increase or decrease of one percent in I would produce a 0.425 percent increase or decrease in the net benefits and a one percent change in R would produce a change of 0.126 percent in the net benefits. Thus, in the area around the optimal solution, the level of the T variable is most critical to the level of net benefits obtained while the level of R seems to not be critical at all.

The particular enterprises making up the optimal enterprise mix for the farms at the optimal solution were examined for any meaningful patterns. The enterprises present in the locally optimal solution were cotton irrigated once, dryland grain sorghum and irrigated alfalfa. Notably these were the same three enterprises present in the programs of all the solution points on the ridge line which are visible in Figure 5. This indicates that this enterprise combination is somewhat more efficient than the other possible combinations in its use of the scarce resources and consistency of yield.

The Interaction Between the Target Delivery and Planned Acres Irrigated

The most meaningful aspect of the response surfaces just examined is the existence of a ridge line of nearly equal net benefits, resulting from an interaction between the delivery target and the planned irrigated acres. To illustrate how and why this interaction occurs, an examination of the way the net benefits were computed will be conducted using the surface represented by Figure 5 for an example. Two solutions found at different combinations of levels of the design variables, namely $T = 5.67$, $I = 7$, $R = 0.150$ (Point I) and $T = 4.33$, $I = 10$, $R = 0.150$ (Point II) will be examined to illustrate the similarities and differences between solution points along the ridge line.³

As was mentioned earlier, the enterprises entering into the optimal solution for almost all points along the ridge line are cotton irrigated once, dryland grain sorghum and irrigated alfalfa. The primary net benefits at each of these points are obtained as the sums of the products of the average net returns from these three enterprises and the amounts of each enterprise used in the optimal solution. Therefore, it is important to understand how the net returns and acreages of each enterprise are determined. First, the

³Understanding of the following description would be aided by reviewing the description of the simulation model in Chapter II.

acreages of each enterprise are determined in the income maximization program developed by Freund [8] . The determination of the acreages of each enterprise used in the optimal solution is influenced by the amount of variance and covariance of the net returns of the enterprises, the size of the risk aversion constant being used and the amount of net returns associated with each enterprise. In Table 9 it can be seen that there is not much difference between the amount of each enterprise in the solutions of the two points examined here. Thus, the amounts of each enterprise present in the solutions will be ignored for the present. Table 9 also shows that the average net returns for the cotton and alfalfa enterprises are slightly different for the two points. Figure 8 shows the year by year net returns for cotton irrigated once for each of the two points along with the yearly rainfall. As can be seen, in the years when the rainfall is greater than 1.5 feet the net returns for point I are greater than the net returns for point II. However, the reverse is true when rainfall is less than 1.5 feet per year, except in a few cases where shortages of irrigation water are experienced. Since the net returns for both points are determined with the same equations (see Tables 6-8) which relate net returns to total annual water available, the differences in net returns, as seen in Figure 8, are due to differences in the amount of water available.

Fig. 8.--Annual net returns per acre for cotton irrigated once from the simulated points I and II and annual rainfall for the 39-year period used in the model

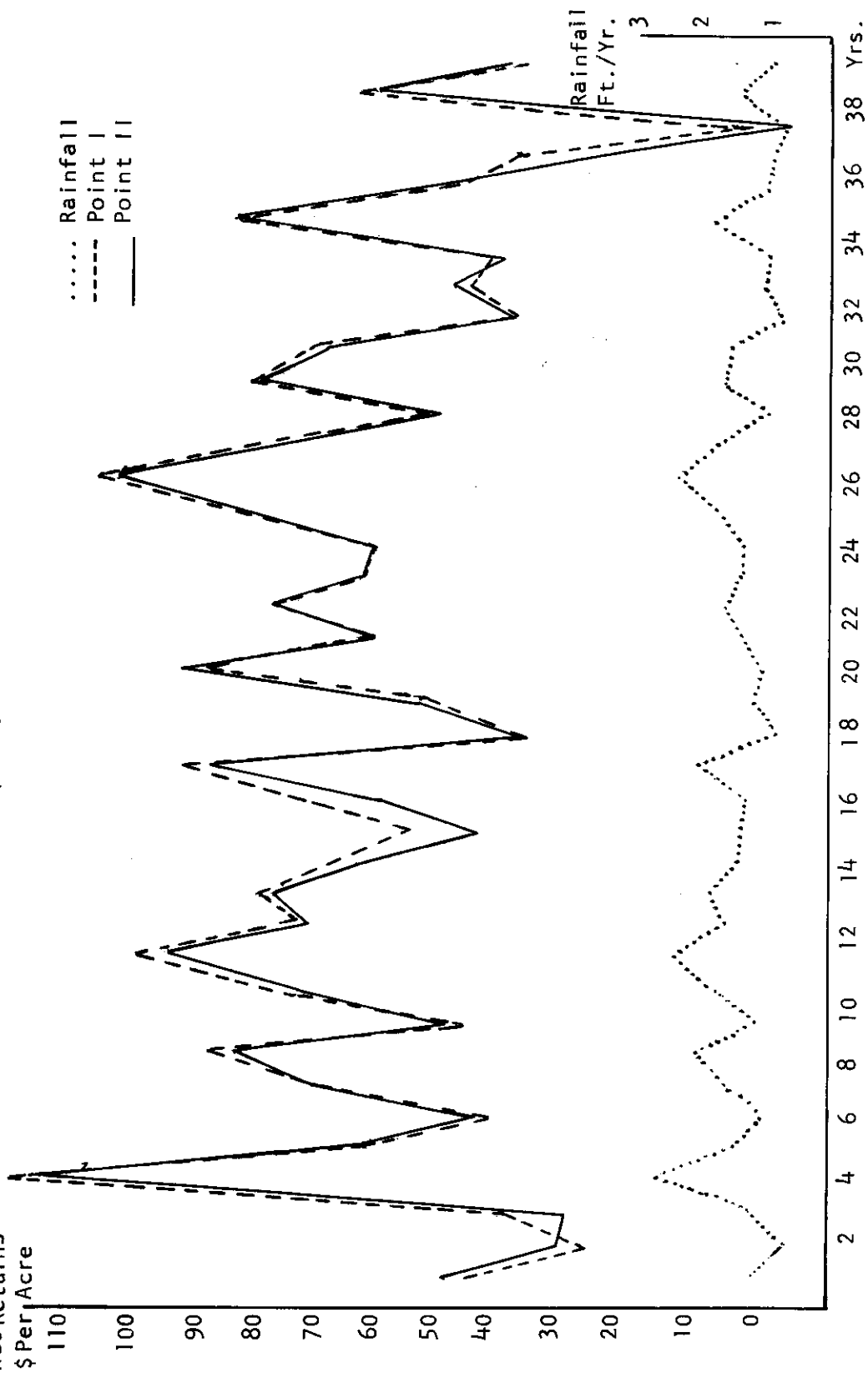


Table 9.--Acres used and net returns of enterprises making up solution: points I and II

	Point I		Point II	
	Acres Used	Ave. Net Returns \$/ac.	Acres Used	Ave. Net Returns \$/ac.
Enterprise:				
Cotton irrigated once (Ac.)	73	63.39	73	62.11
G.S. - dryland (Ac.)	21	11.91	18	11.91
Irrigated alfalfa (Ac.)	192	59.57	197	55.73
Average Amount of Irrigation Water Delivered to the Farm (Ac. Ft.)	421		414	
Primary Net Benefits (\$1,000)	-89		-112	

The amount of water available is a function of the delivery target, the amount of rainfall, the amount of acres planned for irrigation, normal irrigation water requirements and shortages in the amount of irrigation water available if any. The manner in which all of these variables are related in the determination of the total available water for the enterprise is explained in Chapter II. Generally speaking, however, increasing the level of the delivery target increases the amount of water delivered per acre of planned irrigation and decreasing the acres of planned irrigation decreases the total amount of water delivered to each farm. Thus, on the average, the amount of water delivered to the farm is about the same for point I as it is for point II (See Table 9). It follows then that the average net returns from each enterprise would also be about the same and, if costs were not different, the primary net benefits would be about the same. Thus, the existence of the ridge-line.

The Effects of Risk on the Primary Net Benefits

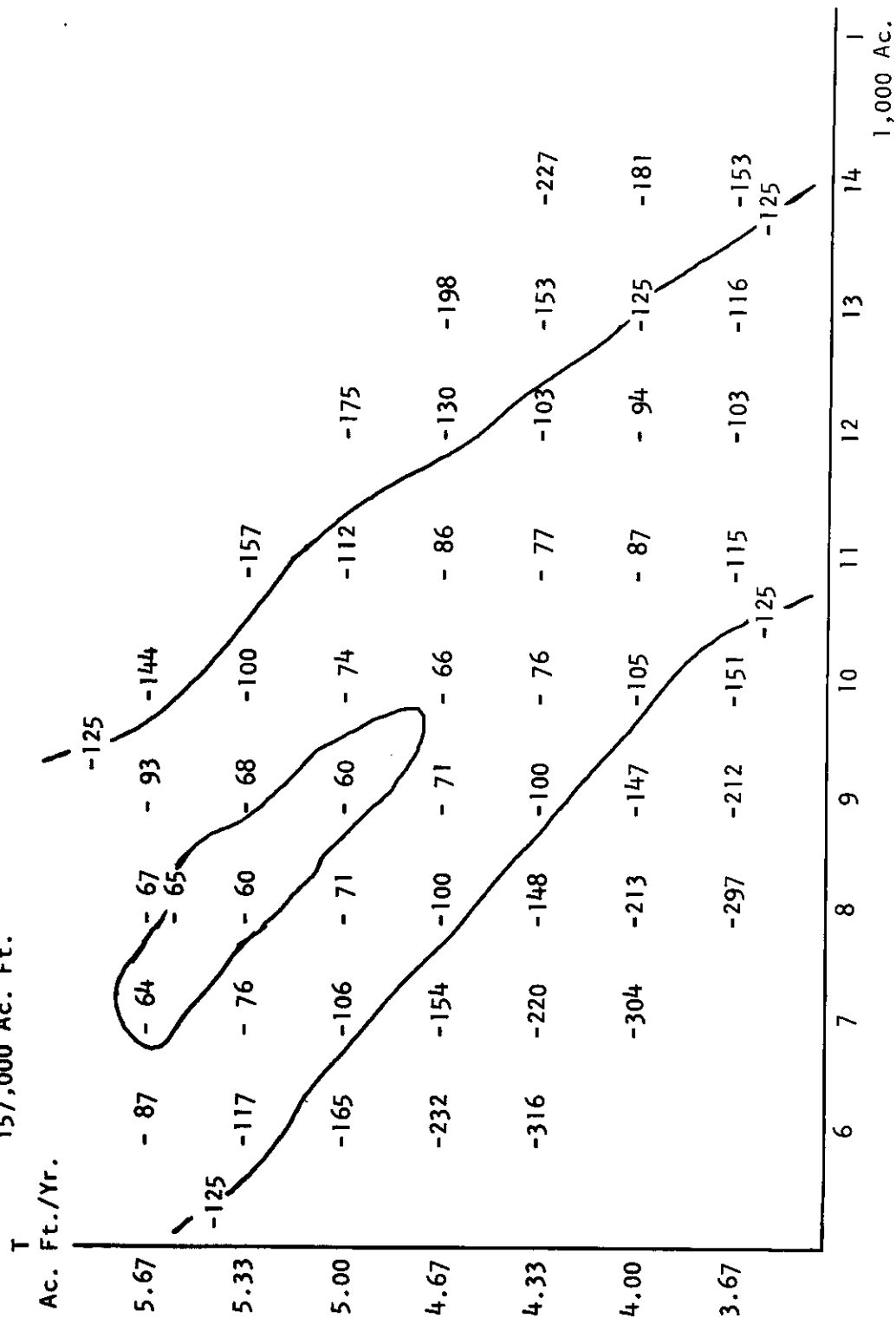
As was discussed earlier in this study the most reasonable level of the risk aversion constant (α) seemed to be 0.00005. However, the consequences of choosing this particular level of α over some other level could not be ascertained unless the net benefits response surfaces were generated using other α levels in the model. For this reason, the effects of all 336 combinations of levels of the design variables were simulated using three additional levels of α . The levels used were $\alpha = 0$, $\alpha = 0.0001$ and 0.0002. The level $\alpha = 0$ represents no risk aversion, the other levels represent high risk aversions and were chosen arbitrarily as twice and four times as large as the original α level of 0.00005.

The response surface for $\alpha = 0$ can be represented mathematically as

$$B_{20} = -5147.6 + 1260.7T + 463.2I - 1979.0R - 81.3T^2 - 12.2I^2 - 5773.8R^2 - 55.8TI + 379.0TR + 215.2IR \quad (20)$$

where B_{20} , T , I and R are the same as B_{19} , T , I and R in equation 19. The global maximum for this surface is found at $T = 5.2$, $I = 8.14$ and $R = 0.157$ and gives a B_{20} value of -54,000 dollars. This surface is depicted graphically in Figure 9 as a function of T and I only. Although a global optimum exists, the ridge line due to the interaction between T and I is still evident. One should note that at this zero level of α there is no aversion to risk.

Fig. 9.--Annual primary net benefits (in \$1,000) as a function of target (T) and planned acres irrigated (I) using a risk aversion constant of $\alpha = 0$ and a reservoir capacity of 157,000 Ac. Ft.



Therefore, the model ignores income variations completely and the solution is the same as would be obtained from a standard linear programming solution of $\bar{N}'X$ only (see equation 13).

The response surface for $\alpha = 0.0001$ can be represented as

$$B_{21} = -4155.0 + 619.8T + 645.0I = 4032.4R - 16.7I^2 - 6453.9R^2 \\ - 82.9TI + 690.3TR + 322.6IR \quad (21)$$

where B_{21} , T , I and R are the same as in equations 19 and 20. This surface, like equation 19, has no obtainable global maximum because the matrix of first partial derivatives is not negative definite. Again, the ridge of near constant net benefit levels due to the interaction between T and I , is evident in this response surface. This surface can be seen in Figure 10 as a function of T and I . Although an apparently significant saddle point is shown in this figure, examination of the actual data from which this surface was estimated suggests that the saddle point is the result of a poor fit of the data, and not a result of the increased α level.

The mathematical representation of the surface for $\alpha = 0.0002$ is

$$B_{22} = -14988.2 + 4256.3T + 1231.9I - 5388.8R - 306.3T^2 - 26.5I^2 \\ - 6992.2R^2 - 180.3TI + 999.7TR + 387.1IR \quad (22)$$

where B_{22} , T , I and R are defined as in equations 19, 20 and 21. This surface can be seen in Figure 11 also as a function of T and I . Again the ridge of constant net benefits is seen as a significant feature of the surface.

Fig. 10.--Annual primary net benefits (in \$1,000) as a function of delivery target (T) and planned acres irrigated (I) using a risk aversion constant of $\alpha = 0.0001$ and reservoir capacity of 150,000 Ac. Ft.

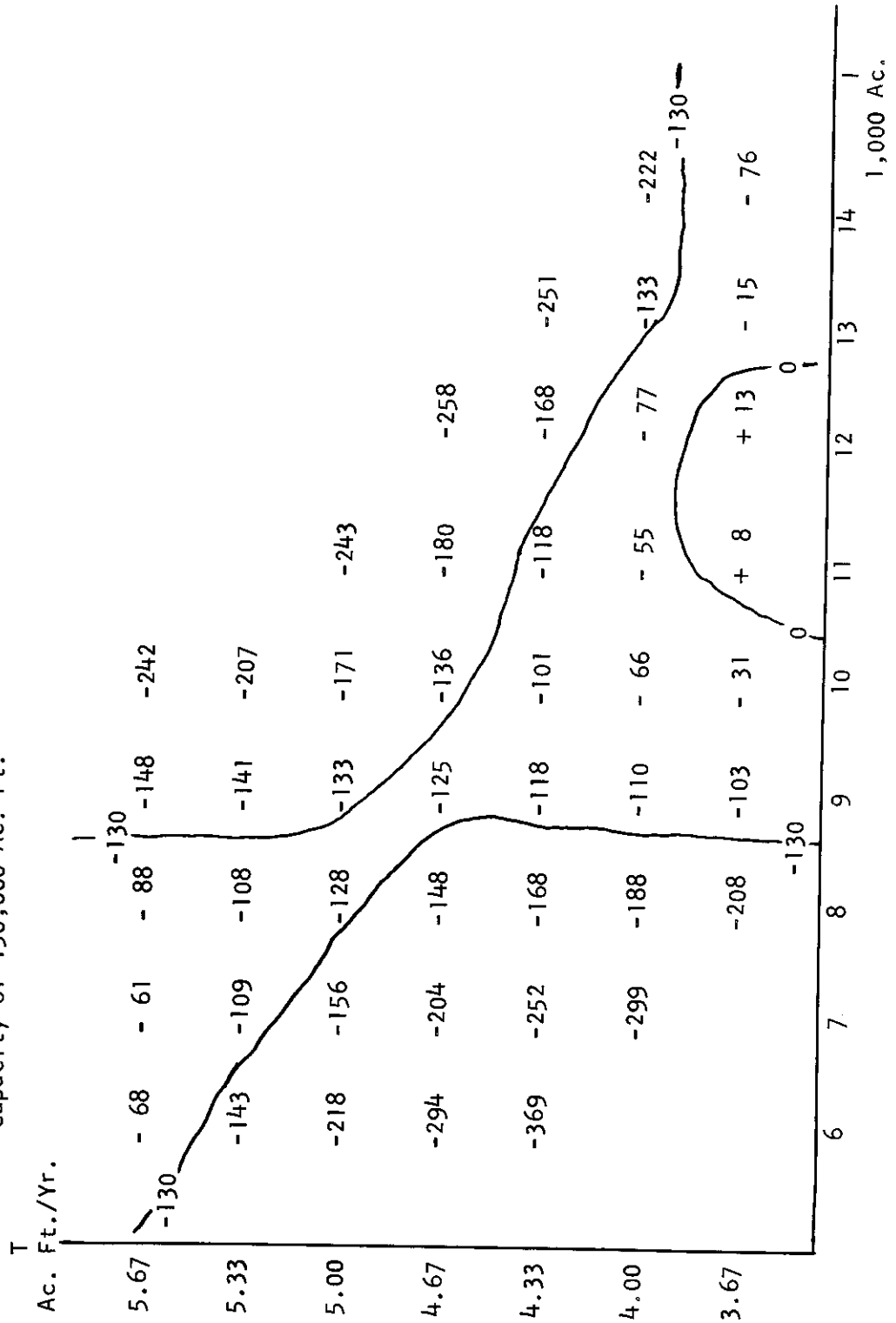
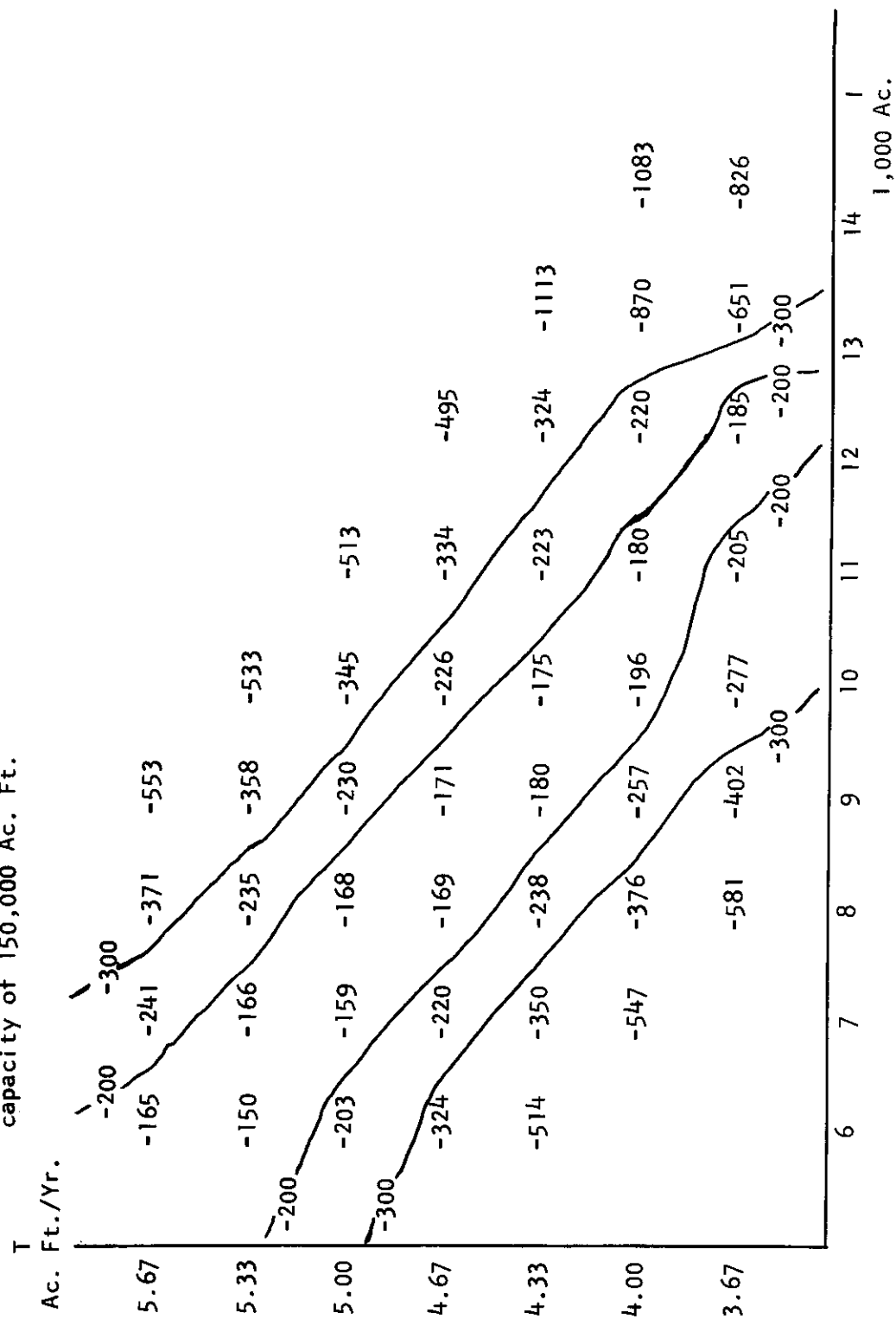


Fig. 11.--Annual primary net benefits (in \$1,000) as a function of delivery target (T) and planned acres irrigated (I) using a risk aversion constant of $\alpha = 0.0002$ of reservoir capacity of 150,000 Ac. Ft.



Generally, as the risk aversion constant increases, the surfaces become steeper. That is, the difference between net benefits from locations on the ridge of optimal solutions and the net benefits from other locations becomes greater as α gets larger. This can be seen in Table 10 and by comparing the surface for $\alpha = 0.0005$ with the surface for $\alpha = 0.0002$ shown in Figures 8 and 11 respectively. In Figure 11, the ridge line

Table 10.--The effects of different levels of farmers aversion to risk on the design variables

Item	Level of Risk Aversion Constant	
	$\alpha = 0.0005$	$\alpha = 0.0002$
Optimal Levels of Design Variables:		
T (Ac. Ft.)	5.67	5.3
R (1,000 Ac. Ft.)	150	150
I (1,000 Ac.)	7	6
Value of Net Benefits at Local Optimum (\$1,000)		
	-89	-150
Enterprises		
Cotton Irrigated Twice (Ac.)	73	73
Dryland Grain Sorghum (Ac.)	21	0
Irrigated Alfalfa (Ac.)	192	159
Percent of total land used (%)	100	81

is much sharper and more pronounced than in Figure 8. One should note that while there is quite a difference in the size of the optimal net benefits, the local maxima of both surfaces are located very nearly the same. That is, for the $\alpha = 0.0005$ surface the local maximum is found at $T = 5.67$, $I = 7$ and $R = 0.150$ while for the $\alpha = 0.0002$ surface the local maximum is at $T = 5.3$, $I = 6$ and $R = 0.150$. This would seem to indicate that although the

response surface changes appreciably, the relevant optimal levels of the decision variables hardly change at all when the risk aversion constant changes.

The effect of the size of the risk aversion constant on the choice of, and level of, enterprises entering the optimal solution can also be quite dramatic as is shown in Table 10. A similar phenomenon can be seen in the decrease in the amount of available land used as the risk aversion constant increases. This implies that if a farmer's desire to avoid risk were large enough then he simply would not farm. This point tends to add support to the original contention that a risk aversion constant of no greater than 0.00005 is a realistic level because it allows the farmer to at least use all of his farm land. This contention is valid, of course, only for the particular situation with which this study is concerned.

The effects of the levels of the risk aversion constant imply that water resource system planners would do well to give careful consideration to the ability and desire of the users of the water to accept or avoid risk. This is true because of the effect of risk on the amount of net benefits accruing to society from the system. For example, the optimal annual primary net benefits for this system would be -54,000 dollars if the level of the risk aversion constant were zero while they would be -150,000 dollars if the risk aversion constant were set at 0.0002. This difference of 96,000 dollars per year in primary net benefits to society could hardly be considered

insignificant. On the other hand, if the planners purpose is only to select the optimal combination of the design variables, then the particular size of the risk aversion constant does not appear to be a critical factor.

The Marginal Value Product Returns Response Surface

Assuming that the irrigation water could be sold for a price equal to its marginal value product, the total annual returns to the system, in risk-free dollars, can be determined by multiplying the average annual delivery of irrigation water by its marginal value product. The data necessary to obtain these total annual returns are the marginal value product of irrigation water, from the dual of the quadratic programming algorithm, and the average annual delivery of irrigation water. From these total returns to the system are subtracted the annual repayment of construction costs and the operations, maintenance and replacement costs as in the primary net benefits approach. The results obtained in this manner are the annual net returns to the system from the sale of irrigation water for a specific level of α , T, I and R.

The marginal value product net returns surface, from the data generated using a risk aversion constant of 0.00005 can be represented mathematically as

$$Y_{23} = -2968.8 + 703.2T + 320.5I - 3026.8R - 47.1T^2 - 10.5I^2 - 7814.3R^2 - 44.2TI + 651.7TR + 313.0IR \quad (23)$$

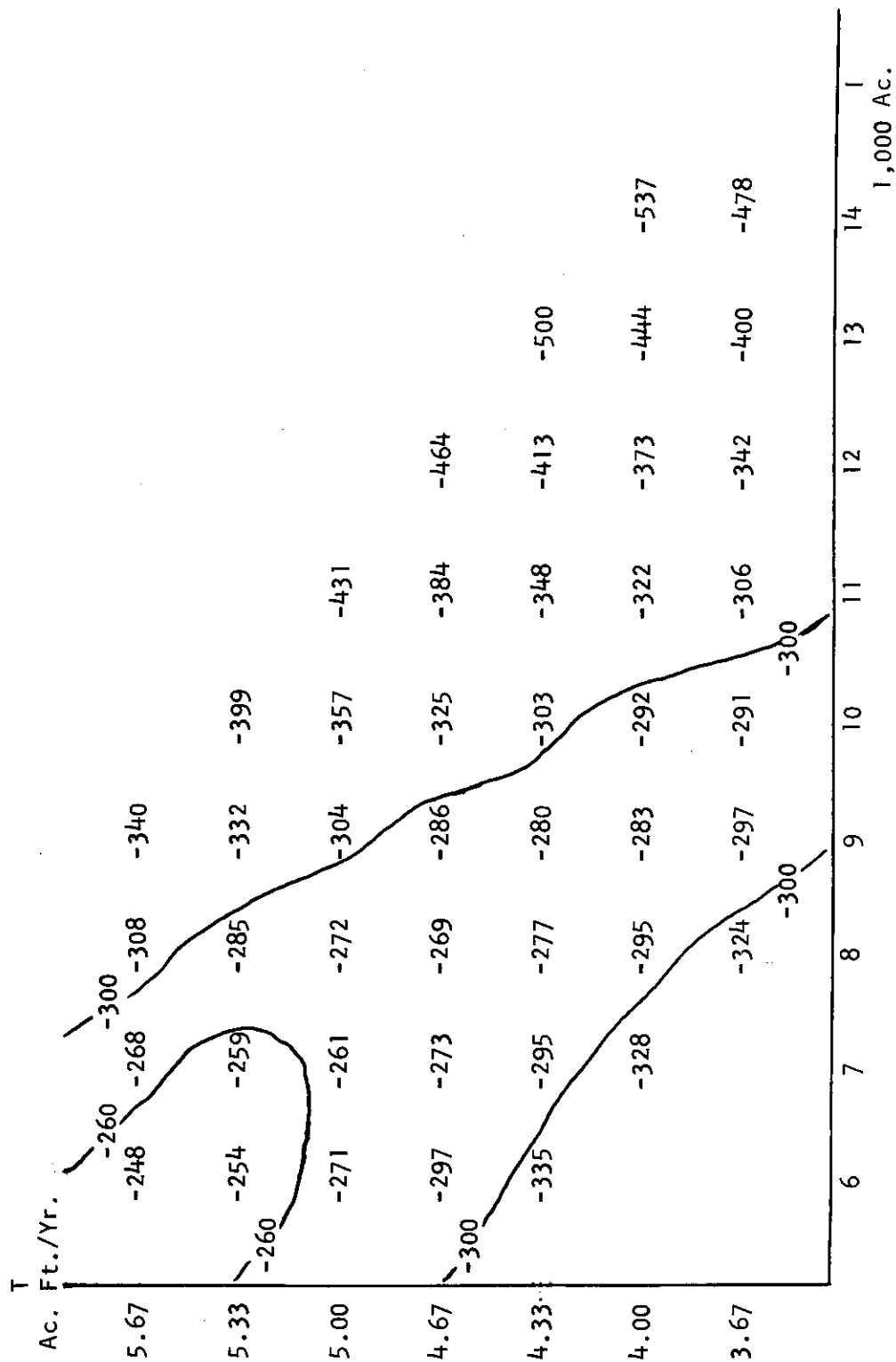
where

Y_{30} = the annual net returns to the water resource system from the sale of irrigation water in the thousands of risk-free dollars, and T , I and R are the same as described in equation 19.

The local maximum for this surface, as illustrated in Figure 12, is at $T = 5.67$, $I = 6$ and $R = 0.150$ and produces an annual net return of -248,000 risk-free dollars. Note that a ridge line due to the interaction between the total annual water target and the planned acres irrigated, similar to the one in the primary net benefits surfaces, is present in this surface also. The ultimate explanation for the existence of the ridge line also lies in the fact that deliveries of water to the farm are almost constant for all points along it. Indeed, the local maxima obtained by the two approaches are at almost the same location. That is, the net benefits surface local maximum is located at $T = 5.67$, $I = 7$ and $R = 0.150$ while the local maximum for the marginal value product surface is located at $T = 5.67$, $I = 6$ and $R = 0.150$. This seems to indicate that either the marginal value product or the net benefits approach would serve the purpose of obtaining optimal levels of the design variables equally well.

The sensitivities of this local maximum with respect to the three decision variables are $T = 0.02$, $I = 0.22$ and $R = 0.12$. These values indicate that the immediate area of the local maximum is rather flat in all dimensions and that little loss or gain in annual

Fig. 12.--Marginal value product net returns (in \$1,000) as a function of delivery target (T) and planned acres irrigated using a risk aversion constant of $\alpha = 0.00005$ and a reservoir capacity of 150,000 Ac. Ft.



net returns would result from small changes in any of the three decision variables. Graphs depicting the response surface as functions of T and R and I and R are shown in Figure 13 and 14 respectively. As in the net benefits approach, they reveal no particularly meaningful patterns to the author.

It should be noted that the actual value of the marginal value product net returns is of little significance since it is given in risk-free dollars. The value of the risk-free dollars relative to actual dollars is somewhat unpredictable because it depends on such factors as the value of the risk aversion constant and the variances and covariances of the particular enterprise included in the optimal enterprise mix for the farm. The level of annual net returns relative to other sample points (different combinations of levels of T, I and R) is, however, important as an indicator of the optimal combination of levels of the decision variables.

The Effects of Risk on the Marginal Value Product Net Returns

To consider the effects that the level of the risk aversion constant might have on the marginal value product net returns response surface, three values of α other than 0.00005 were considered as in the primary net benefits approach. Again, the α values considered were $\alpha = 0$, $\alpha = 0.0001$ and $\alpha = 0.0002$.

Fig. 13.--Marginal value product net returns (in \$1,000) as a function of delivery target (T) and reservoir capacity (R) using a risk aversion constant of $\alpha = 0.00005$ and planned acres irrigated = 6,000

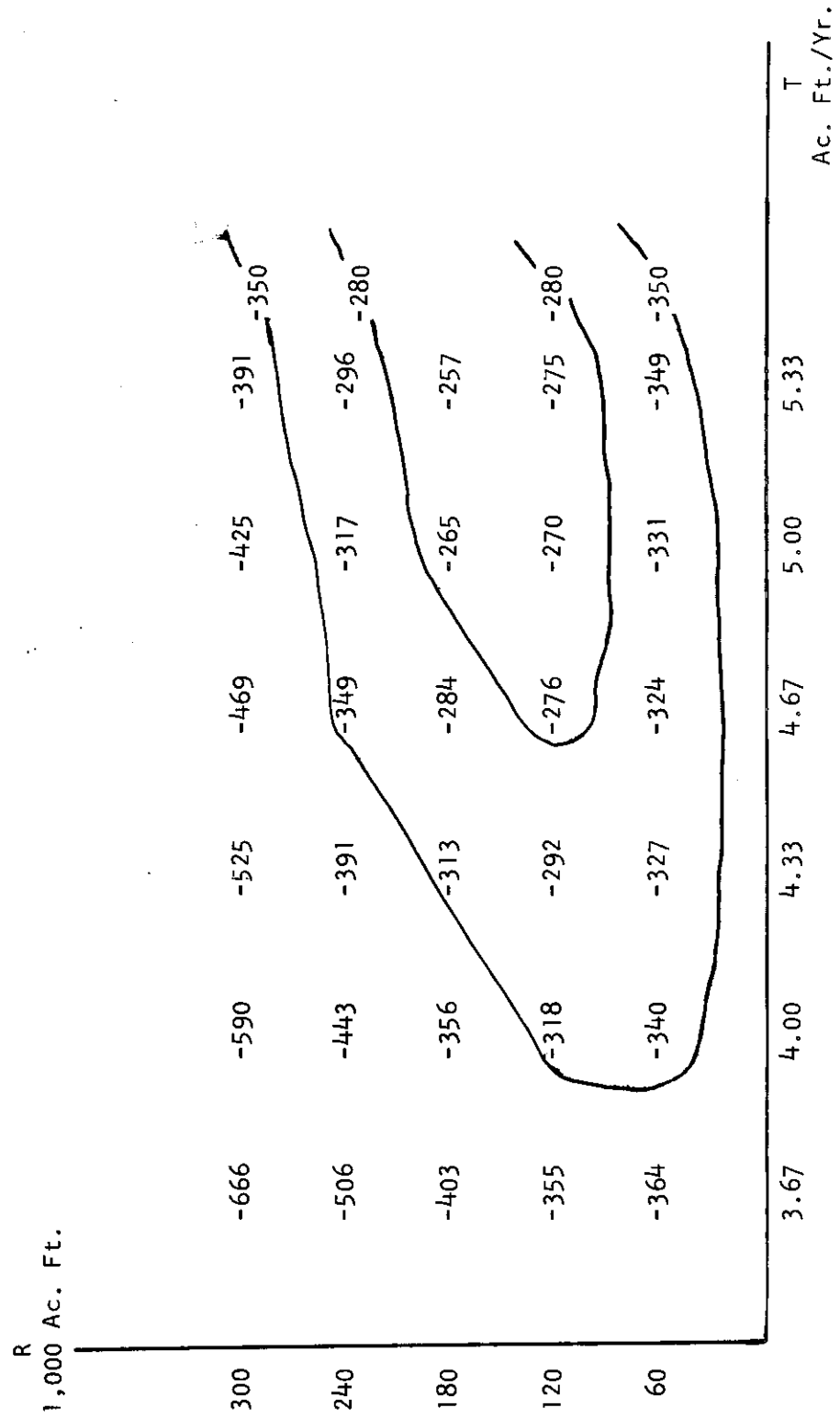
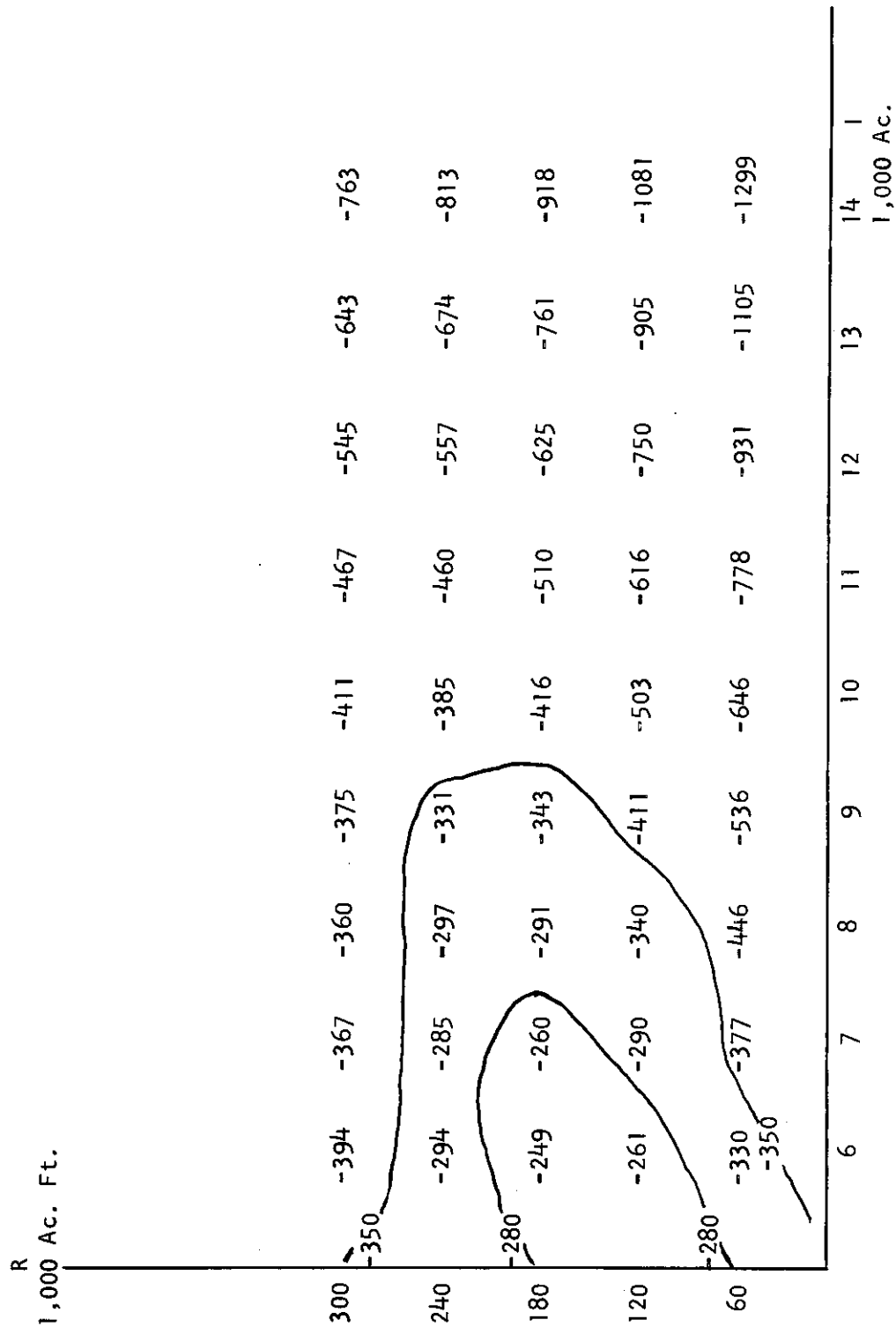


Fig. 14.--Marginal value product net returns (in \$1,000) as a function of reservoir capacity (R) and planned acres irrigated (I) using a risk aversion constant of $\alpha = 0.00005$ and a delivery target = 5.667 Ac. Ft.



The response surface for $\alpha = 0$ can be represented mathematically as

$$Y_{24} = -1291.3 + 223.5T + 78.1I - 2711.5R = 16.5T^2 - 4.0I^2 - 3959.4R^2 + 430.1TR + 190.7IR \quad (24)$$

where Y_{24} , T , I and R are defined as in equation 23. This surface, as depicted in Figure 15, is somewhat different from the surface for $\alpha = 0.00005$ in that the local maximum occurs at $T = 5.67$, $I = 9$ and $RC = 0.180$. Examination of the actual data generated by the simulation model indicates that this optimal level which is quite different from all that have been obtained previously, is the result of a poor fit of the generated data and not a response to the decrease in the α level. This being true, little else can be said about this estimated surface.

The mathematical representation of the surface for $\alpha = 0.0001$ is

$$Y_{25} = -4050.9 + 1072.5T + 480.7I - 4196.9R - 75.6T^2 - 14.0I^2 - 12072.2R^2 - 798TI + 1083.7TR + 445.7IR \quad (25)$$

where, again Y_{25} , T , I and R are defined as in equation 23. The local maximum marginal value product net returns for this surface, as illustrated in Figure 16, is at $T = 5.33$, $I = 6$ and $R = 0.180$. The strong interaction between T and I is again present in this surface as is evidenced by the ridge line of near equal returns. The response surface for $\alpha = 0.0002$ can be represented mathematically as

Fig. 15.--Marginal value product net returns (in \$1,000) as a function of delivery target (T) and planned acres irrigated (I) using a risk aversion constant of $\alpha = 0$ and a reservoir capacity of 180,000 Ac. Ft.

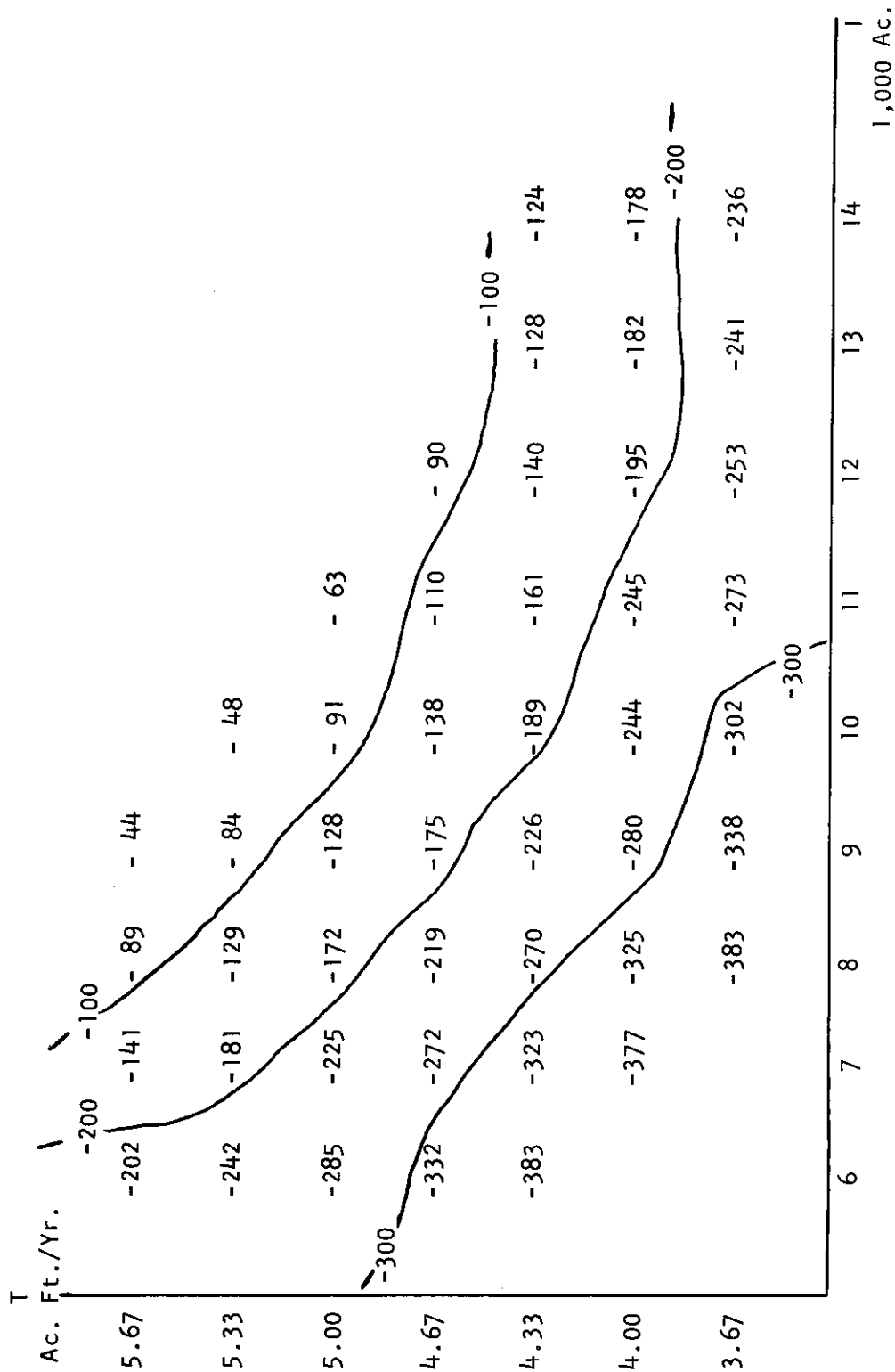
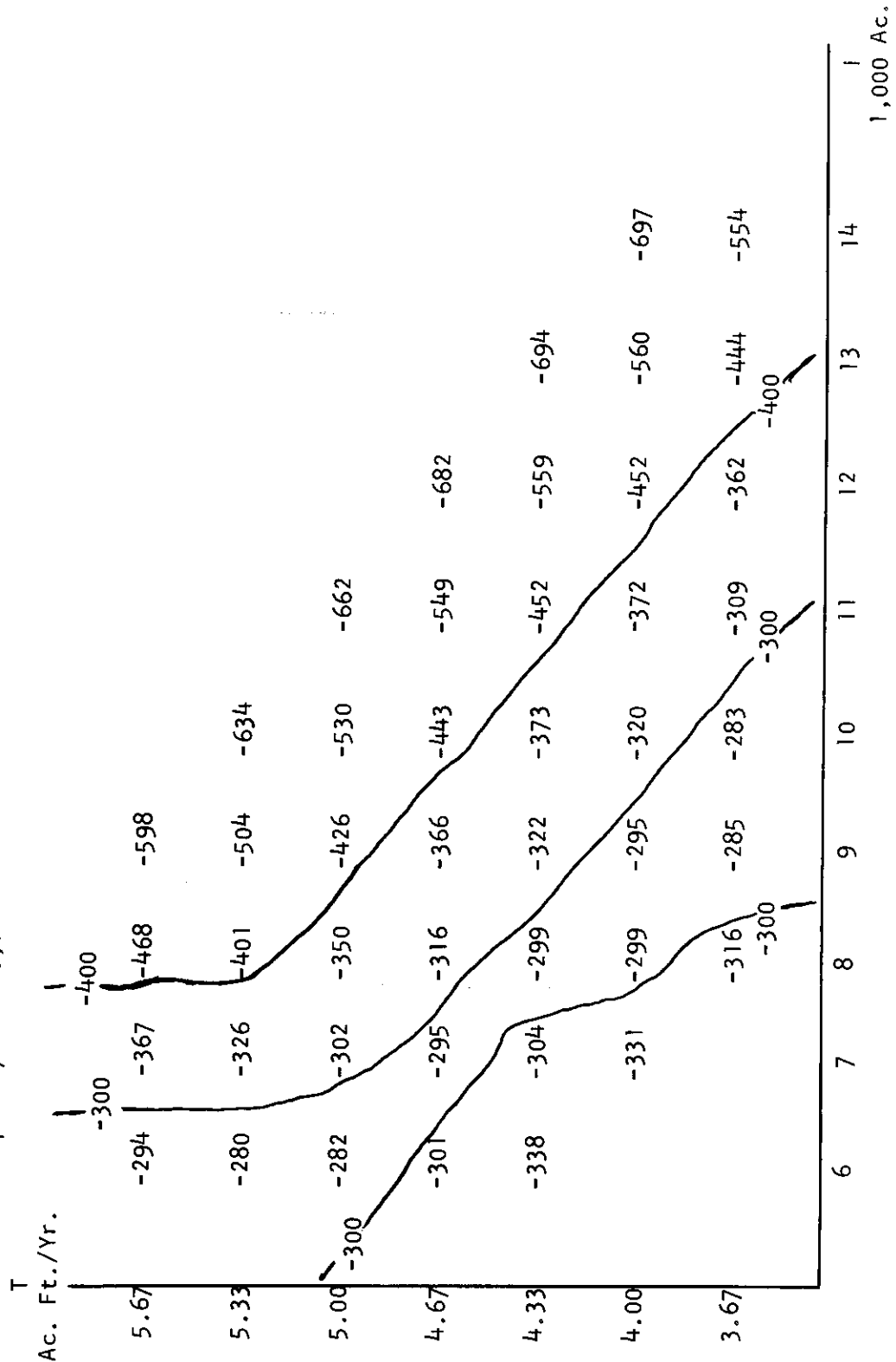


Fig. 16.--Marginal value product net returns (in \$1,000) as a function of delivery target (T) and planned acres irrigated (I) using a risk aversion of $\alpha = .0001$ and a reservoir capacity of 180,000 Ac. Ft.

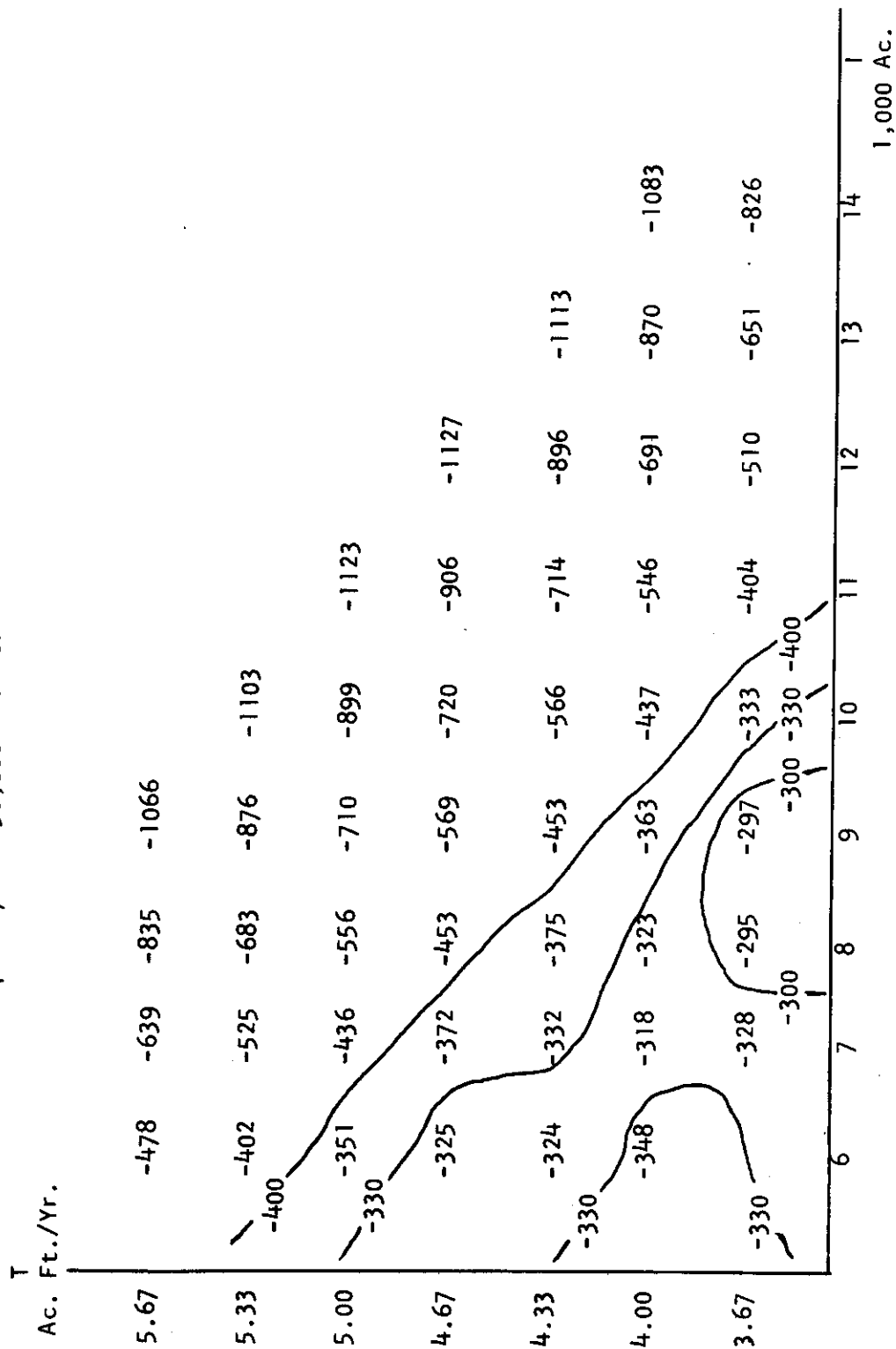


$$Y_{26} = -5975.9 + 1629.9T + 671.8I - 112.1T^2 - 17.4I^2 - 11680.6R^2 - 114.7TI + 425.4TR + 286.9IR \quad (26)$$

where Y_{26} , T , I and R are defined as in equation 23. As can be seen in Figure 17, the interaction between T and I is also prominent in this surface. Although the local optimum is located at $T = 3.67$, $I = 8$ and $R = 0.150$, there is only 26,000 risk-free dollars difference in this point and the point $T = 4.3$, $I = 6$ and $R = 0.150$.

Generally, the effects of risk on the marginal value product net returns response surface are about the same as the effects of risk on the net benefits surface. That is, the ridge line due to the interaction of T and I become more pronounced and the slopes become much steeper as the α level increases. One difference in the effects of risk on the two surfaces is that the optimal values of the marginal value product net returns do not decrease as sharply with increased levels of α as do the optimal net benefit values. This indicates that the marginal value product of water at the optimal solution points is changed relatively little by the size of the risk aversion constant used. In other words, it seems that, at least in the areas near the optimal solution levels of the design variables, the marginal value product of water is relatively insensitive to changes in the levels of the risk aversion constant.

Fig. 17.--Marginal value product net returns (in \$1,000) as a function of delivery target (T) and planned acres irrigated (I) using a risk aversion constant of $\alpha = 0.0002$ and a reservoir capacity of 150,000 Ac. Ft.



Comparison of the Primary Net Benefits Approach
and the Marginal Value Product Approach

The optimal solution of the primary net benefits approach can be interpreted to indicate the actual or realistic average annual net benefits that would result from the system being built and operated at the specified levels of the decision variables. This is true only if all of the assumptions inherent in the simulation model are met. It should be noted, however, that some of the assumptions and data used in this study are not realistic.

The marginal value product net returns represent the expected returns from the irrigation water if it were all sold at its marginal value product. The marginal value products used here are in risk-free dollars which are not necessarily the same as the marginal value product in actual dollars. However, the risk-free marginal value product is, for the surface with $\alpha = 0.00005$, usually within ten percent of the actual marginal value product. The difference is greater than ten percent for the larger α values.

By comparing the marginal value product net returns with the primary net benefits (Figures 5 and 12) it can be seen that the marginal value product returns are, for all points, considerably smaller. This is, in some cases, due to the fact that we are using risk-free values rather than actual dollar values. The main reason for this difference, however, is that the marginal value products produced by this program indicate only the value that would be

added by an additional acre-foot of irrigation water. Naturally, as long as the law of diminishing returns holds, this is less than the value of the units previously used. Furthermore, if all of the irrigation water available to the farm is not used then an additional acre-foot is worth nothing. Thus, for such cases as this, the marginal value product is zero, and the reported returns from water are zero. This is, of course, unrealistic because some of the available water is used, and from the primary net benefits approach it can be seen that it is worth something.

When comparing these two approaches to the problem of obtaining the optimal values of the design variables, one must conclude that there is little difference as is evidenced by comparing the optimal levels from Figures 5 and 12. The primary net benefits approach is, however, superior for the purpose of obtaining realistic estimates of net benefits or net returns to society. From the data presented here it also appears that the net benefits approach produces smoother, more consistent response surfaces which makes evaluation of different combinations of levels of design variables easier and more accurate than is true of the marginal value product net returns approach. This is due primarily to the fact that for some combination of levels of the design variables, particularly those remote to the optimal combinations, the marginal value product of water is zero because water is not a limiting factor at

those points. Since this results in zero returns being computed for the system at these points the marginal value product surfaces are not as smooth and consistent as the net benefits surfaces.

CHAPTER V

Summary

This study illustrates that, within limits, a water resource system planning model can be developed which incorporates the full effects of the risk elements inherent in the system. That is, the water users' reactions to risk and the effects of these reactions on the optimal levels of the design variables can be included in a simulation model of a water resource system. This is accomplished by allowing the users of the water to react to different degrees of variation in the water supplied them by the system and then evaluating the effects of the users reactions on the returns accruing to the system.

This study also explores and compares two basic methods or approaches for evaluating the relative economic efficiency of the many combinations of levels of the design variables. The first, and most useful, was termed the primary net benefits approach. This approach entails the development of a function such that the net benefits from the system for each possible combination of levels of the design variables can be determined. Then, by evaluating a large sample of all the possible combinations, the levels of the design variables which produce the maximum net benefits can be selected.

The second approach entails treating the system as if it were a business firm whose purpose is to maximize profits, or minimize losses. By assuming that the system can sell all of its water at the marginal value product of the water in use, the returns to the system can be determined by multiplying the amount of the water supplied by its marginal value product. The marginal value product is determined at the operating margin of the user firms as the value of the last unit of water used. From the returns to the system, thus obtained, the costs of the system are subtracted leaving the net returns to the system as the remainder. These net returns are determined for a large sample of all combinations of levels of the design variables thus allowing the combination yielding the maximum net returns to be selected.

The results obtained from this study indicate that the net benefits approach generally produces more reliable information than the marginal value product approach. In addition, the results show that the amount of net benefits that society can expect from the operation of a water resource system, such as the one simulated here, depends to a great extent on the degree of reliability with which the water can be furnished its users. These net benefits are also influenced by the users' desires to avoid risk in the form of variations in income. Most important, however, the study reveals that the optimal levels of the relevant design variables of a system such as this one are not appreciably affected by the degree to which the water users wish to avoid risk.

Limiting Assumptions

Several assumptions are made in this study which limit the applicability of the results to more general situations and the adaptability of the methods to other uses. The most limiting of all of the assumptions, at least from the author's point of view, is the assumption that net returns from the crop enterprises can be determined as a function of the total water available per year without regard to its availability at different times during the year. This assumption is not realistic for it is well known that the amount and distribution of water during the growing season is more important in determining crop yields than is the gross amount of water available. The full effect of this assumption on the general applicability of the results is indeterminate. That is, it is impossible to determine how the net benefits from the various combinations of levels of the design variables might change, or if they would change at all, if the assumption was modified to account for the timeliness of water availability during the year. Certainly, the assumption should be modified before trying to adopt the methods used in this study to uses in other studies.

Other limiting assumptions in this study include the operating rule which requires that all water be supplied to the users without regard to future shortages, and the rule that requires that all of the water be proportionately applied to each enterprise in the farmer's optimal enterprise mix regardless of how much or how little

is available. These two assumptions undoubtedly differ from realistic operational procedures. The effect that they have on the net benefits accruing to a system such as this one appears to be that of causing the calculated net benefits to be less than could be expected if they were replaced by more realistic assumptions. Similar effects on the results reported in this study are due to the assumption limiting the water from the system to only one use and the assumption which limits the size of the irrigation development to a maximum of 20,000 acres.

Although all of these assumptions limit the degree to which the results reported in this study can be applied to similar situations none of them represent serious faults in the basic methodology developed here. In fact, in any simulation model of a water resource system, similar assumptions of one form or another, together with the specific hydrologic and cost data used, tend to limit the general applicability of the results.

Analytical and Data Limitations

The method of analysis used in this study is simulation. However, the simulation model incorporates several other analytical techniques as parts of the whole model. Perhaps the most significant aspect of the model is the use of Freund's procedure for incorporating the effects of risk into a constrained income maximization program. This analytical technique, when incorporated into the overall model, allows for the full impact of the

hydrologic risk elements in the system to be analyzed and incorporated into the final decision as to the optimal level of the design variables.

The model, however, is not without its limitations. Although it incorporates the effects of risk, and the water users' reactions to risk, it does not deal at all with uncertainty. That is, the effects of such factors as unexpected changes in price levels, changes in government policies and programs and new technological developments are not analyzed in the model.

Additional limitations are placed on the model developed in this study by a lack of available data. For example, the assumption that net returns from the crops are a function of the total water available per year was made because there was not enough data available regarding the effects of the distribution of water over time on crop yields. The implications of this assumption were discussed in the previous section. Data regarding the water users' desires to avoid risk, or, the proper size of the risk aversion constant, were also not available. This lack of data was partially circumvented in this study by obtaining some reasonable indications of the maximum level of the farmers' desires to avert risk. However, such indications might not always be obtainable; in which case, lack of data regarding the water users' feelings about risk would negate the use of the methods developed in this study for incorporating risk into a planning model.

This study illustrates that the method, or approach, for evaluating the economic efficiency of a water resource system which assumes that the water from the system is sold at its marginal value product is seriously deficient. That is, the marginal value product net returns approach to determining the optimal levels of the design variables and the economic efficiency of the system is inadequate in many respects. Most significant is the failure of this method to provide meaningful indications of the exact level of the actual returns to the system. This failure is due in part to the fact that the marginal value products obtained from the income maximization program are in terms of risk-free dollars rather than actual dollars. However, if the marginal value products were in actual dollars, the fact that they are determined by the marginal value product of the last unit of water used, means that the price assigned to the water would be of less value than all but the last unit of it was actually worth to the farmers. Thus, the marginal value product net returns would still not account for the total value of the water. Due to these limitations, the author recommends that future studies of this sort use the net benefits approach to determining the economic efficiency and optimal level of the design variables of the system being studied.

Conclusions Concerning Future Investigations

Future research directed toward improving water resource system planning models could make significant contributions through any one of several types of studies. One significant contribution that could be made would be to find a method whereby the model developed in this study could be made to account for the effects of water availabilities over periods of time such as months rather than years. Recent work by Anderson [1] and Anderson and Maass [2] on a technique for estimating crop response to water might be incorporated into the model developed here in such a manner as to introduce the effect of the timeliness of water availability. If a realistic method of estimating the influence that water available on a monthly basis has on net returns from crops could be obtained, then the basic methods developed in this study would have great promise as an operational planning procedure.

Many other modifications of this study could be made which would undoubtedly provide more realistic estimates of the net benefits from a water resource system. One such modification would be to make the rule governing the delivery of water to the irrigation district more realistic. That is, to change it so that water could be held in reserve when the reservoir level began to get low to insure that the reservoir would not run dry.

A particularly appealing aspect of this model is the ease with which the system could be expanded. For example, other

uses of the water from the reservoir, such as supplying industrial and municipal water, could be included in the system. Also, restrictions on the reservoir level might be imposed in order to incorporate flood prevention and/or recreation demands on the system. Other extensions of the model could undoubtedly be proposed, but these will serve to illustrate the range of possible extensions that could be incorporated into this model.

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APPENDIX A

Table A-1.--Stream flow of South Concho River at San Angelo in 1,000 acre feet

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1916	5.0	3.2	1.7	4.3	2.0	0.5	0.4	0.4	8.3	2.1	1.8	2.2	31.9
17	2.8	2.1	.5	.5	.2	.2	.3	.3	2.2	.2	.2	.2	9.7
18	.4	.6	.4	.2	15.6	6.8	.4	.2	.2	11.0	1.2	1.7	38.7
19	2.5	1.4	.8	.8	10.3	44.5	31.0	5.0	6.3	20.6	4.8	3.7	131.7
1920	4.4	4.5	2.3	1.1	.9	6.8	.4	6.4	4.4	2.5	2.9	2.3	38.9
21	2.2	.9	1.9	.8	.8	4.4	.4	2.0	.8	.2	.1	.1	14.6
22	.2	.2	.2	177.1	65.3	6.8	16.3	.4	.3	.2	.6	1.4	269.0
23	2.1	4.1	4.2	5.3	2.2	.4	1.2	4.2	15.6	12.2	9.7	5.8	67.0
24	4.9	4.2	5.1	21.8	26.8	6.4	.5	.3	3.5	2.6	2.1	3.5	81.7
1925	2.7	1.9	1.0	10.0	62.3	7.6	2.3	5.0	4.9	4.1	2.1	2.7	107.4
26	3.1	2.1	4.7	51.0	11.0	3.7	1.0	4.2	.2	4.7	2.1	7.8	95.6
27	3.7	3.7	3.8	1.5	1.1	.8	.7	.5	.8	19.1	1.3	2.3	39.3
28	2.5	1.4	1.1	.8	3.2	10.7	1.0	5.1	1.4	2.2	2.6	2.7	34.7
29	2.5	1.5	2.9	8.4	4.6	.9	.5	.5	1.9	9.5	1.8	1.5	36.5
1930	1.7	1.2	.8	2.2	1.2	9.3	0	0	.1	100.3	6.3	5.9	129.0
31	4.1	7.4	3.1	4.0	2.8	1.6	2.8	1.7	1.2	.1	1.4	1.6	31.8
32	2.8	2.5	1.9	5.6	77.7	8.2	29.4	2.4	24.2	9.1	7.3	7.4	178.5
33	7.8	5.9	4.9	3.0	3.4	.6	.1	.1	.4	.9	2.5	1.8	31.4
34	2.5	2.1	2.2	7.1	.7	.3	0	3.0	0	0	2.0	1.1	21.0

Table A-1.--Continued

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1935	1.2	7.1	.5	3.8	52.8	29.0	6.2	1.9	24.7	4.1	4.2	3.5	139.0
36	2.8	1.8	1.5	.3	12.3	1.6	1.0	0	429.7	19.7	7.1	9.9	487.7
37	6.2	4.8	5.2	2.8	14.2	15.1	1.3	.4	1.0	1.5	1.6	9.3	63.4
38	12.3	5.0	3.1	18.9	3.6	2.0	115.3	6.6	2.7	2.3	2.9	3.6	178.3
39	4.0	3.1	2.9	3.9	16.3	2.5	3.2	5.2	.7	1.7	1.9	2.9	48.3
1940	2.6	3.2	2.0	6.2	4.1	15.7	3.0	4.6	3.2	1.8	3.4	3.5	53.3
41	3.4	3.5	11.4	10.9	38.3	56.7	10.5	10.8	7.9	21.0	11.5	10.0	195.9
42	8.2	6.0	5.6	7.5	4.8	2.3	.9	54.2	14.0	8.2	7.2	6.9	125.8
43	6.7	4.8	4.7	3.3	5.7	2.2	.9	0	1.9	2.8	2.1	3.5	38.6
44	4.2	4.6	3.8	1.1	2.6	3.4	0	.4	17.7	2.9	1.4	2.5	44.6
1945	2.9	2.7	2.7	4.9	.7	0	29.0	.9	1.0	4.1	2.4	2.5	53.8
46	3.0	2.5	1.2	3.8	1.2	2.2	0	.6	38.1	7.2	2.4	8.5	70.7
47	3.8	2.0	2.6	1.3	5.4	5.4	0	0	0	0	.3	1.5	22.3
48	.7	2.0	.1	1.1	7.0	1.4	34.7	0	11.3	1.0	.5	.7	60.5
49	1.2	2.1	5.6	70.2	16.3	7.8	0	0	2.3	13.9	2.4	2.0	123.8
1950	2.6	1.7	.7	.6	.8	2.0	0	2.5	10.2	0	.3	.9	22.3
51	.2	.9	.5	.1	0	1.5	0	7.0	0	0	.2	.5	10.9
52	.6	.1	.4	.7	5.0	0	0	.3	.4	.8	.5	.5	9.3
53	.6	.6	15.4	0	9.5	0	4.6	12.9	2.6	15.5	.6	.2	62.5
54	.4	.3	.3	24.2	17.2	13.4	.3	0	0	--	--	--	56.1
Total	125.5	109.7	113.7	471.9	509.9	284.7	299.6	150.0	646.1	310.1	105.7	128.6	3,255.5
Mean	3.2	2.8	2.9	12.1	13.1	7.3	7.7	3.8	16.6	8.0	2.7	3.3	83.5

Table A-2.--Effective precipitation at San Angelo, in inches

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1916	.31	0	0	3.23	1.57	2.65	1.04	1.06	2.43	1.31	.03	.04	13.67
17	.50	.10	.22	.55	2.64	.90	.90	.41	1.86	0	0	0	8.08
18	.60	.35	.39	0	3.21	.51	.24	.41	1.09	3.56	2.03	2.54	14.93
19	3.71	.68	2.15	1.60	3.63	4.20	3.29	2.52	4.18	4.01	2.15	.56	32.68
1920	2.31	.35	.26	0	1.91	3.64	.59	4.20	1.62	1.80	.67	.14	17.49
21	.51	.81	2.18	.66	2.20	3.49	.28	1.20	.67	0	.07	.14	12.21
22	.50	.11	.48	4.12	3.90	1.83	2.72	.09	1.87	2.20	2.17	0	19.99
23	2.37	3.57	1.48	2.53	1.41	.61	1.12	2.10	1.78	3.23	2.73	1.46	24.39
24	.15	2.07	1.47	.40	3.71	.02	.25	1.02	2.07	.96	.01	1.73	13.86
1925	.12	.20	0	3.35	3.58	1.58	2.67	4.01	2.98	2.42	1.45	.07	22.43
26	2.37	0	3.30	3.28	1.61	2.86	2.48	2.93	1.06	3.10	.35	3.87	27.21
27	.33	2.43	1.72	.37	2.22	1.84	1.53	1.58	2.82	3.96	0	1.06	19.86
28	.93	1.48	.60	1.22	2.93	3.19	2.46	1.81	3.70	1.40	1.01	1.13	21.86
29	.40	.98	2.44	2.17	3.29	.74	.51	.31	2.43	3.15	.49	.71	17.62
1930	.52	0	.65	2.38	2.03	2.19	.26	.74	.76	4.20	1.80	.95	16.48
31	1.84	2.09	.50	2.20	.86	1.02	1.76	.30	.80	2.45	1.53	1.28	16.63
32	1.05	2.53	.49	2.00	4.20	2.90	1.81	3.21	4.20	.28	.84	2.33	25.84
33	.52	.71	.35	.40	3.12	.04	.40	1.70	.78	1.27	.88	.53	10.70
34	1.06	.32	2.61	3.60	1.07	.87	0	1.63	.05	.22	3.55	.13	15.11

Table A-2.--Continued

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1935	.15	2.16	.17	2.02	4.04	3.63	3.93	1.97	4.20	1.56	.93	.80	25.56
36	.33	.14	.35	.72	3.49	.13	3.26	.16	4.20	2.18	.69	1.10	16.75
37	.43	.34	1.39	.64	3.62	3.12	1.97	.75	3.03	2.12	1.09	2.77	21.27
38	2.03	.58	.85	3.75	2.22	1.17	4.12	.40	.16	.65	.70	1.04	17.67
39	1.98	.10	.61	1.48	2.65	.99	1.41	2.40	.49	1.49	2.58	.91	17.09
1940	.48	2.00	.62	2.48	3.35	4.20	.64	.82	2.11	2.37	2.91	.58	22.56
41	1.05	1.11	3.58	3.78	2.07	4.00	2.41	4.20	3.19	3.07	.24	.74	29.44
42	0	.20	.42	3.32	3.63	1.58	.85	4.03	2.65	3.66	.19	1.63	22.16
43	.35	.20	1.04	.39	2.96	.68	.75	.19	2.85	.40	1.93	1.92	13.66
44	2.79	1.15	.59	.44	3.78	.31	.26	3.40	3.77	2.48	1.20	1.97	22.14
1945	.58	1.39	1.01	3.17	.60	2.12	3.60	1.92	1.56	2.81	.15	.39	19.30
46	1.96	0	.38	.96	.12	.97	.10	.17	2.33	1.37	.80	1.47	10.63
47	1.91	.16	1.35	1.87	2.84	1.74	.11	.30	0	1.14	.89	.76	13.07
48	.21	.87	.02	1.07	1.73	1.78	3.11	.16	1.10	1.40	.49	.14	12.08
49	2.13	1.73	1.02	3.71	2.31	2.57	.78	1.49	2.26	3.33	0	1.49	22.82
1950	.37	.34	.05	1.85	3.29	1.27	.84	2.32	3.65	.06	0	0	14.04
51	.03	.56	.47	.55	1.10	3.65	.75	2.26	1.25	.14	.16	.31	11.23
52	.08	.39	.68	1.06	2.43	.07	1.10	.05	.89	0	1.53	.56	8.84
53	.03	.16	4.00	.94	2.37	.65	3.22	1.76	1.23	3.98	.06	.13	18.53
1954	.51	.03	.34	2.86	3.57	2.55	.17	.12	.24	.44	.28	.05	11.16
Total	37.50	32.39	40.23	71.12	101.26	72.26	57.69	60.10	78.31	74.17	38.58	37.43	701.04
Mean	.96	.83	1.03	1.82	2.60	1.86	1.48	1.54	2.01	1.90	.99	.96	17.98

Table A-3.--Effective evaporation rate at San Angelo, in feet per unit surface area

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1916	.11	.18	.57	.25	.67	.74	.76	.67	.38	.42	.29	.30	5.34
17	.21	.30	.45	.64	.56	.87	.86	.80	.43	.60	.33	.24	6.29
18	.08	.26	.59	.68	.57	.75	.93	.88	.54	.16	.21	0	5.65
19	-.14	.21	.16	.39	.28	.14	.50	.53	.05	.09	.21	.28	2.70
1920	.14	.34	.42	.56	.44	.31	.75	.11	.40	.32	.27	.35	4.41
21	.26	.25	.17	.56	.48	.33	.64	.71	.49	.50	.37	.37	5.13
22	.24	.35	.51	.16	.24	.51	.71	.81	.56	.30	.16	.23	4.78
23	.10	-.05	.29	.25	.57	.65	.70	.60	.38	.15	.04	.19	3.87
24	.22	.12	.24	.51	.27	.87	.76	.76	.36	.33	.45	.03	4.92
1925	.20	.35	.48	.15	.31	.67	.64	.17	.24	.26	.14	.22	3.83
26	.05	.33	.05	.06	.38	.56	.46	.43	.41	.11	.30	-.23	2.91
27	.16	.04	.38	.62	.71	.57	.69	.70	.29	.02	.31	.11	4.60
28	.19	.12	.49	.57	.29	.57	.56	.36	.24	.38	.13	.11	4.01
29	.16	.10	.32	.44	.30	.70	.66	.71	.35	.20	.22	.24	4.40
1930	.08	.32	.40	.35	.50	.58	.89	.68	.62	-.23	.13	.06	4.38
31	.05	.05	.32	.23	.49	.71	.62	.68	.67	.28	.10	.06	4.26
32	.11	.08	.45	.42	.03	.36	.62	.47	-.28	.36	.27	.03	2.92
33	.23	.18	.45	.62	.56	.88	.74	.50	.48	.36	.23	.25	5.48
34	.17	.28	.27	.28	.70	.89	.97	.71	.63	.52	-.01	.24	5.65

Table A-3.--Continued

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1935	.28	.16	.48	.49	.23	.29	.38	.57	.01	.33	.17	.13	3.52
36	.22	.23	.57	.56	.30	.78	.53	.83	-1.39	.21	.23	.12	3.19
37	.14	.28	.27	.53	.33	.50	.69	.67	.21	.30	.21	-.03	4.10
38	.14	.16	.43	.18	.59	.58	.39	.77	.61	.44	.30	.21	4.80
39	.11	.25	.34	.53	.47	.84	.75	.45	.68	.40	.08	.16	5.06
1940	.13	.12	.49	.45	.44	.20	.84	.53	.52	.24	.08	.14	4.18
41	.13	.14	.04	.14	.29	.22	.45	.21	.19	.12	.27	.12	2.32
42	.19	.27	.47	.23	.41	.60	.74	.21	.28	-.04	.31	-.03	3.64
43	.19	.33	.35	.63	.41	.66	.57	.89	.36	.43	.13	.02	4.97
44	-.02	.16	.38	.62	.30	.75	.73	.55	.22	.28	.19	.02	4.18
1945	.14	.11	.35	.27	.74	.72	.23	.53	.45	.06	.29	.18	4.07
46	.01	.23	.36	.51	.61	.63	.82	.77	.25	.24	.17	.07	4.67
47	.11	.21	.17	.31	.33	.60	.85	.62	.63	.34	.16	.20	4.53
48	.12	.11	.40	.55	.54	.60	.46	.72	.46	.30	.30	.28	4.84
49	-.06	.07	.30	.06	.30	.47	.65	.52	.28	.09	.31	.09	3.08
1950	.18	.22	.52	.42	.27	.58	.52	.52	.10	.40	.35	.26	4.34
51	.25	.22	.47	.56	.57	.42	.73	.64	.50	.46	.32	.28	5.42
52	.22	.32	.46	.52	.56	.96	.70	.87	.49	.49	.20	.18	5.97
53	.35	.30	.21	.60	.62	.91	.76	.50	.56	.09	.32	.23	5.45
54	.28	.52	.49	.38	.64	.85	1.17	.97	.77	.54			(6.71)
Total	5.73	8.22	14.66	16.28	17.30	23.82	26.42	23.62	13.42	10.85	8.54	5.71	167.86
Mean	.15	.21	.38	.42	.44	.61	.68	.60	.34	.28	.22	.15	4.42

APPENDIX B

Table B-1.--Simulation results for $\alpha = .00005$ and total annual water target = 5.0 feet per year

Planned Acres Irrigated (1,000)	Reservoir Capacity in Acre Ft. (1,000)	Average Annual Irrigation Water Deliveries to Each Farm in Acre Feet	Primary Net Benefits Dollars (1,000)	Marginal Value Product of Irriga- tion Water in Risk Free Dollars
6	300	333	-325	28.5
	240	333	-263	28.5
	180	333	-201	28.5
	120	331	-185	27.5
	60	316	-181	23.1
	0	123	-490	0
8	300	436	-217	25.2
	240	434	-166	23.9
	180	432	-131	23.6
	120	421	-111	22.2
	60	381	-137	14.6
	0	138	-507	0
10	300	524	-169	7.0
	240	520	-117	6.4
	180	506	-102	4.8
	120	481	-119	1.1
	60	427	-183	0
	0	150	-520	0
12	300	581	-269	0
	240	571	-255	0
	180	553	-236	0
	120	524	-247	0
	60	456	-397	0
	0	157	-529	0
14	300	613	-415	0
	240	602	-371	0
	180	586	-336	0
	120	555	-403	0
	60	476	-542	0
	0	161	-493	0
16	300	635	-603	0
	240	624	-586	0
	180	605	-565	0
	120	573	-585	0
	60	489	-602	0
	0	163	-496	0

Table B-1.--Continued

Planned Irrigated Acres (1,000)	Reservoir Capacity in Acre Ft. (1,000)	Average Annual Irrigation Water Deliveries to Each Farm in Acre Feet	Primary Net Benefits Dollars (1,000)	Marginal Value Product of Irri- gation Water in Risk Free Dollars
18	300	649	-756	0
	240	637	-716	0
	180	615	-687	0
	120	581	-672	0
	60	497	-625	0
	0	163	-500	0
20	300	650	-839	0
	240	643	-783	0
	180	618	-730	0
	120	585	-696	0
	60	502	-661	0
	0	162	-502	0

VITA

James Richard Conner

Personal Data

Born: June 22, 1942, Coryell Co., Texas
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 Dependents: Wife, Neta; Son, Michael

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May 1960: Graduated from Evant High School Evant, Texas
 January 1965: Received B.S. Degree (Agronomy), Texas A & M University, College Station, Texas
 January 1967: Received M.S. Degree (Statistics), Texas A & M University, R. J. Freund Committee Chairman
 January 1970: Received Ph.D. Degree (Agricultural Economics), Texas A & M University, R. J. Freund and M. R. Godwin Committee Co-Chairmen

Experience

1967-1969: Employer-Texas A & M University, Institute of Statistics
 Title-Research Associate
 Duties-Evaluated water resource system designs under conditions of hydrologic and economic risk by applying operations research techniques.
 1967: Employer-Texas A & M University, Department of Agricultural Economics and Sociology
 Title-NDEA Fellow
 Duties-Full-time Graduate Student
 1965-1966: Employer-Texas A & M University, Institute of Statistics
 Title-Research Assistant
 Duties-Tested the feasibility of adopting multiple frame sampling techniques to the estimation of agricultural statistics.
 1965: Employer-Statistical Reporting Service-USDA, Austin, Texas
 Title-Agricultural Statistician
 Duties-Recruited employees and assisted in gathering agricultural data.

"The typist for this dissertation was Mrs. Sandy Davis."