OPTIMAL IRRIGATION MANAGEMENT STRATEGY UNDER HYDROLOGIC AND IRRIGATION EFFICIENCY UNCERTAINTY REGIMES

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CHARLES NWACHUKWU UDEH
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AUTHORIZATION TO PROCEED WITH THE FINAL DRAFT:

This thesis of Charles Nwachukwu Udeh for the Ph.D. degree with major in Agricultural Engineering and titled "Optimal Irrigation Management Strategy under Hydrologic and Irrigation Efficiency Uncertainty Regimes," was reviewed in rough draft form by each Committee member as indicated by the signatures and dates given below and permission was granted to prepare the final copy incorporating suggestions of the Committee; permission was also given to schedule the final examination upon submission of two final copies to the Graduate School Office:

Major Professor John R. Busch Date 4/10/78

Committee Members C C Warnick Date 4/11/78

W. W. Fitzsimmons Date 4/11/78

Date 4/11/78

C E Brockway Date 4/11/78

REVIEW OF FINAL DRAFT:

Department Head W. W. Fitzsimmons Date 4/24/78

College Dean ______ Date ______

FINAL EXAMINATION: By majority vote of the candidate's Committee at the final examination held on date of April 24, 1978 Committee approval and acceptance was granted.

Major Professor John R. Busch Date 4/24/78

GRADUATE COUNCIL FINAL APPROVAL AND ACCEPTANCE:

Graduate School Dean ______ Date ______

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ABSTRACT

The irrigation efficiency concept is crucial in irrigation systems design, planning, and management. It is used in determining total irrigation water requirements and in sizing the irrigation system components. Irrigation efficiency is not a deterministic parameter; the occurrence and sequencing cannot be predicted with complete reliability. Realistically, it is a probabilistic phenomenon subject to large spatial and time variabilities, and hence uncertain.

A Bayesian decision theory optimization model was developed that explicitly incorporated the uncertainties inherently associated with the probabilistic hydrologic and irrigation efficiency phenomena. Specifically, the model selected that optimum acreage to be seasonally committed to irrigation, controlled by those probabilistic events in conjunction with the irrigators' risk and uncertainty response characteristics.

The developed model was applied to the Wood River Valley Irrigation District No. 45, located in Blaine County, Idaho. Major inputs into the model included stochastic irrigation diversions, probabilistic irrigation efficiency regimes, three crop response functions, utility functions, irrigated crop production cost and crop price functions, consumptive use and seasonal crop yield coefficients. Both single and multi-crop systems were modeled under an unimproved gravity irrigation system.

The optimal management strategies generated using the model closely conform to the present practices in the district. Using Baye's theory, the optimal strategy developed under a "lack of knowledge" situation

was improved as new data on irrigation efficiency became available.

The generated optimality was sensitive to and dependent upon the probability density functions for irrigation efficiency regimes, the crop response functions, the decision objective criteria, and the seasonal crop yield coefficients. The cost assessed for irrigation water use, and the irrigated crop production cost input functions were not as critical in influencing optimal results generated by the model as the probabilistic hydrologic and irrigation efficiency parameters.

The developed and tested model is a valid tool for optimal irrigation decision making under both the hydrologic and irrigation efficiency uncertainty regimes.

CHAPTER I

INTRODUCTION

Water has been described as "a vital but absolutely scarce unevenly distributed, nonhomogenous commodity, very imperfectly costed, its use controlled by complex laws, and administrative ruling, its uses extraordinarily interdependent and its market value little understood" (Dychman, 1964).

Water is a unique resource derived from a complex hydrologic system. It consistently continues to play a vital role in human life patterns, and its availability both in time and space, in adequate quantity and acceptable quality largely determines the behavior and utility of other important natural resources. Consequently, water is both central and instrumental in local, regional, and national economic development. Whether in a developing or already developed economy, water resources exert a great control on economic growth. (Buras, 1972).

In the underdeveloped regions of the world, water is traditionally and erroneously assumed abundant and thus does not control economic growth. Thus, the surplus water resource is somewhat beneficially but inefficiently used as a production input.

Throughout the world today, the magnitude of water problems are becoming increasingly obvious and incredibly enormous often necessitating complete revision of traditional concepts, water rights, and wasteful attitudes. World regions are undergoing rapid demographic, economic, social and technological transformations. Such factors as increasing industrial growth, growing urban population, and increasing per capita income have greatly intensified water use. Consequently, the demand for available water resources has greatly increased. Forecast water use trends developed on the basis of historic total demands by such huge users as domestic, industrial, agricultural, and municipal indicate that the available water supply may, in fact, be limiting. In some areas, water shortages to a degree affecting economic growth are actually occurring.

An era of rapidly growing population naturally implies that a food and fiber production growth must also be generated and regularly maintained roughly in equilibrium with the ever increasing population. However, suitable environmental and climatic conditions are essential input factors for increased food and fiber production, and water is the most important resource that can provide and enhance such desirable conditions.

Thus, water is absolutely vital to agricultural production, particularly in arid and semi-arid regions where naturally occurring precipitation seldom completely supplies crop water requirements. Although the gross seasonal rainfall in humid areas is often generally more than adequate for optimum crop production, sometimes, however, rainfall sequences are completely out of phase with the critical crop growth stages. This situation frequently leads to severely depressed crop yield unless supplemental irrigation water is supplied during those critical periods.

Irrigation activities utilizing water as a key production input have meaningfully transformed the economy of the arid and semi-arid regions of the United States (Doming, 1968). In these regions, irrigated agriculture is the major consumptive water user accounting for over 85 percent of the total water supply that is beneficially used (Framjii and Mahajan, 1969).

In an era of competing and largely incompatible water uses, optimization of the entire water resources system would be very beneficial. However, the modeling and the optimization of a large-scale comprehensive water resources system that eventually yields efficient overall optimal strategy is definitely a difficult task.

The best approach appears to be to begin with optimizing the irrigation systems first since these systems are considered as sub-systems entirely contained within the superior and larger "host" water resources system. Even very small improvements in the water use pattern and management of an irrigation system would significantly enhance optimality of the entire water resources system. Upon this concept is based the motivation for this study.

CHAPTER II

COMPONENTS OF WATER RESOURCES SYSTEMS

2.1 WATER RESOURCES SYSTEMS

Water resources planning and development involve a multidimensional complex problem array that is largely derived from the rapidly increasing requirements and demands currently being imposed on most water projects.

Large-scale water resources projects must be properly conceived, effectively planned, efficiently constructed, and adequately managed and operated in such a manner as to completely achieve specified national water resources objectives. All Federal water projects must now be appraised on the basis of a common or uniform format that strongly emphasizes and demands full cognizance of the impacts and overall ramifications of such projects on the national economic development, social well-being, regional development, and environmental quality (Water Resources Council, 1973).

These vital water resources objectives frequently in conflict and seldom easily amenable to quantification, present extremely complex problems to planners and decision makers who must now abandon the orthodox benefit/cost function of evaluating water projects (Maass et al., 1962). As both tangible and intangible benefits and costs are usually associated with various water resources projects, an entirely new systematically consistent methodology must be developed and used for assigning relative weights to the many noncommensurable component effects. This implies that, in order to achieve a competent optimal design, the noncommensurable factors must be reduced to a common denomination of effectiveness.

However, if no realistic methodology exists for assigning values to intangible social and political factors, their effects upon the water resources system can be determined by specifying them as boundary conditions (Buras, 1972).

Furthermore, large-scale water resources projects must recognize, consider, and harmonize all the various water uses both consumptive and non-consumptive such as flood control, navigation, power developments, agriculture and instream uses (Figure 2-1). This implies that all water uses must be fully considered in the allocation of available water. Since within the last two decades, ecologists have expressed deepest concern for the environment, increasing focus has recently been directed toward water quality, pollution, and environmental protection and enhancement.

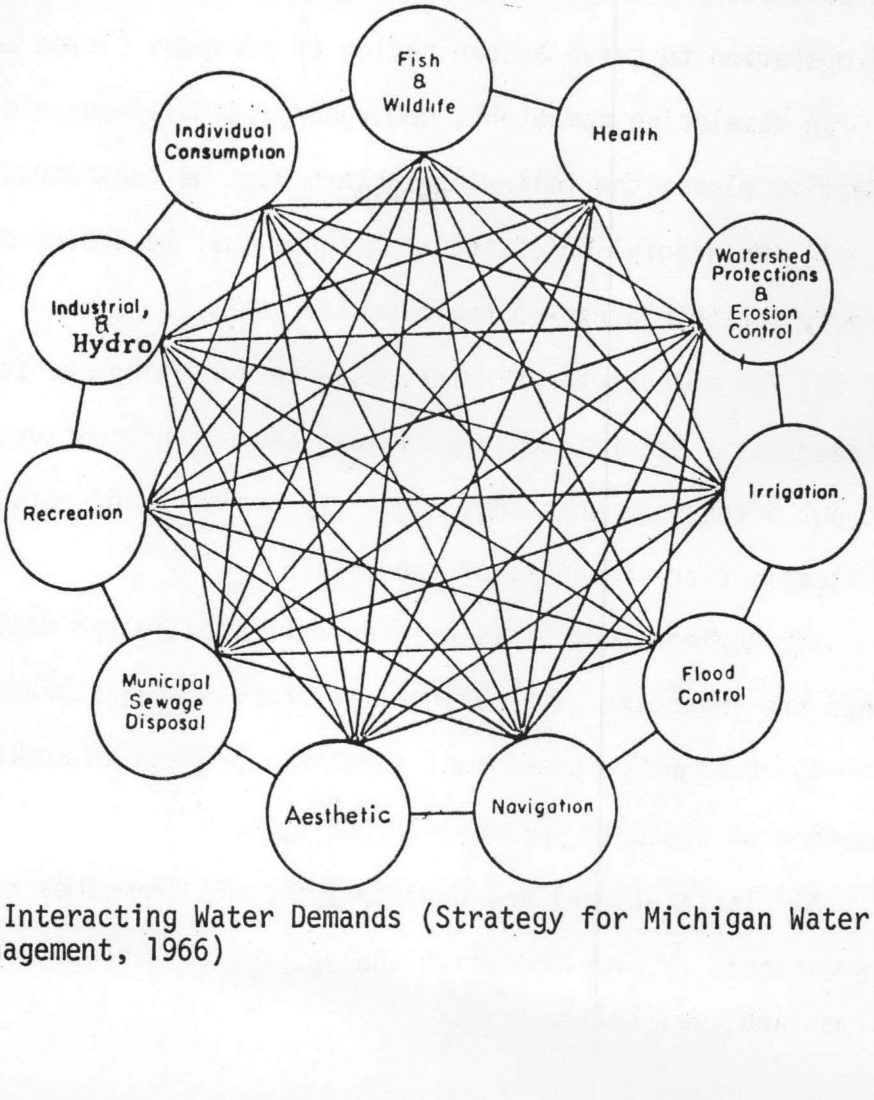


Figure 2-1. Interacting Water Demands (Strategy for Michigan Water Resources Management, 1966)

Viewed in entirety, water resources development clearly implies a comprehensive fully integrated basin-wide approach that views the overall problem array as a unit rather than on a separate component basis. The water resources planner must also admit he has lost command and authority over a sizable unlimiting water supply that more than meets demand and breeds inefficiency of use. He now has to adopt a new and more comprehensive approach, that is, one that combines planning of water resources with planning of the various production complexes and services that depend on water as a crucial input (Wiener, 1972).

In short, the planners new attention must now be directed toward comprehensive, multi-objective and multi-purpose project designs that are completely and efficiently integrated in planning, construction, and operation to serve a combination of purposes (James and Lee, 1971).

In developing competent, comprehensive multi-purpose and multi-objective plans, the following factors must be considered:

1) Meaningful objective techniques must be employed for weighting largely intangible non-economic social goals.

2) The objectives of water resources planning are too complex to be adequately determined by political and administrative processes alone without a feedback unit that regularly monitors and relays the social implications or tradeoffs of the plan.

3) Regional conflicts must be reflected in the design where local needs are invariant with national or professional standards.

4) Design decisions must sometimes proceed in the absence of complete or adequate information and data.

5) Institutional and budgetary factors sometimes constrain implementation or even objective analysis of certain alternatives (James and Lee, 1971).

It therefore, follows that multi-objective, multi-purpose and comprehensive water resources development generates a host of largely interdependent and regularly interacting physical, sociological, biological, legal, political and geographical decision fronts that create, as resultants, engineering, socio-economic, and ecological interfaces (Hall and Dracup, 1970). These interfaces create complex problem components generally associated with the development, control, allocation, treatment, and utilization of water resources (Buras, 1972). Most planners have traditionally regarded water resources as a mere physical system comprising only the total physical water and land resources. Economists have alternatively viewed the planning problem on the basis of economic efficiency, designed to provide the manager with the most economical path to follow dictated by least cost or maximum benefit functions. Water resources management has also been looked upon as a social tool designed to resolve conflicts of interest between groups in the use of water and related resources. Any single perspective, whether physical, economic, or social is inadequate to completely describe water resources management or represent the various decision processes that must be considered.

Meaningful solutions to such a socio-economic and politically complex problem mix spanning such a huge area transcend the capability of a single discipline (de Neufville and Marks, 1974). An interdisciplinary team that would attempt to synthesize and integrate the various techniques and viewpoints from the various participating fields is mandatory.

This team would be faced with decisions concerning the development and utilization of water resources such as the optimal size of water resources systems components to construct, and the timing and optimal scale of development. Once the system has been built, the operating strategies, the appropriate institutional setting that would ensure its efficient functioning under specified socio-economic restraints would become potential decision fronts. The associated ecological impact in terms of water quality and water resources depletion must also be considered as pertinent team decisions.

It is difficult to determine in advance which disciplines should be represented in the team. The scope and character of the problem would usually determine the type and extent of involvement. However, close association between water resources and the following traditional fields have been observed; agricultural engineering, hydrology, economics, public administration and law (Buras, 1972).

2.2 IRRIGATION SYSTEMS WITHIN A WATER RESOURCES ENVIRONMENT

An irrigation system may be regarded as a sub-system that is entirely physically and socio-economically located within an encompassing superior and larger water resources environment. It, therefore, forms an important integral component within which its various factors are regularly interacting with the "host" water resources system.

Busch (1974) stated that the degree of interaction and integration can be determined by literally incising the irrigation sub-system off the water resources anatomy. By appropriately defining the boundary conditions of the "cut" sub-system, the complex dysfunctions occurring at the boundary, resulting from rather intangible socio-economic factors, would become more apparent for consideration (Wiener, 1972).

As a major consumptive water user within the water resources domain, optimality of the entire water resources system must largely depend on the optimal functioning of the irrigation sub-system. Accordingly, the irrigation sub-system must be optimized both in time and space to achieve an overall realistic optimal design and operation of the encompassing system. Irrigation systems are now expected to incorporate technologically and economically feasible hardwares that induce efficient water use (Idaho State Water Plan, 1974).

To achieve this, Busch (1974), suggested an efficiently designed and effectively operated irrigation system that completely complies with the various historical, physical, and legal input constraints ought to be pursued. That system would become an end product of an effectively integrated complete line or arrangement of the distribution and application system components. As a water resources sub-system, irrigation systems design clearly creates a hydrologic, engineering, economic, legal and social complex problem mix complicating decision making efforts. Engineers once used to postulate that if an irrigation project which proved optimally competent in one location, its engineering and management principles could and ought to be wholly transplanted into another location with similar physical conditions (Smith, 1973).

Experiences from social resistances to project development adequately demonstrate that other non-engineering inputs such as socio-economic factors must also be adequately considered in irrigation systems design (Allison and Jalal, 1974, Committee on Research of Irrigation and Drainage Div., 1974).

Legal problems may arise concerning water rights. Certain irrigation project investments have been made based on a firm assurance of a specific amount of water supply guaranteed or somewhat insured by such water rights. Water allocation decisions in water short seasons have been extremely problematic. The water supply amount guaranteed by certain early water rights generally largely exceeds crop water requirements; a situation that breeds inefficiencies in agricultural water use. Consequently, certain states now include both beneficial and efficient water use clause as an essential and integral component of water rights. Regardless of the doctrine upon which the right is based, riparian, appropriative or a mixture of both, water rights defined as legal certainties do not imply hydrologic certainty.

The water resources decisions concerning agricultural water use are mostly related to the amount and timing of irrigation water application for optimal crop yield. However, both the amount and timing, generally involve rather complex decisions arising from complex interrelationships existing between crop, soil, and water inputs. Such complex decisions most frequently defy traditional pure engineering and economic analyses.

The planning, design, and development of irrigation systems, therefore, require multi-faceted procedures. An interdisciplinary team must be equipped with the proper training and analytical tools for evaluating and selecting alternative actions from a myriad of potential alternatives.

Recently, systems analysis methodology has been advanced and actually employed in tackling complex irrigation and water resources problems.

CHAPTER III
SYSTEMS ANALYSIS OPTIMIZATION TECHNIQUES

3.1 SYSTEMS ANALYSIS

It is rather difficult to exactly mark the official inception of systems analysis. However, a universal agreement exists that systems analysis is a tool that was developed and fostered during World War II due to the vital need to obtain rapid answers to the increased complexity and uncertainty in military decision-making. During the war, weapons had become increasingly complex and more sophisticated and experience was generally lacking in their procurement, handling maintenance, and management. These vital military decisions required comprehensive systems analysis (Meta Systems, 1971).

To deal with the military resource allocation, strategic and technological decision fronts, a team of eleven scientists representing various disciplines was assembled and charged with the duty. This team became known as the Blackett's Circus (Thierauf and Klekamp, 1975).

From the several viewpoints and techniques contributed by respective participant disciplines grew a rather synthetic descipline known as systems analysis. Trefethen (1954), Thierauf and Klekamp (1975), Flagle et al., (1960) present excellent histories of systems analysis.

In the last few decades, the techniques of systems analysis have been successfully utilized in obtaining solutions to many business, industrial, and government problems. Business has become greatly diversified and increasingly complex due to a dynamic environment. The seemingly universal application of systems analysis in most complex problems stems from the literally limitless capability inherent in the approach.

Systems analysis functions by breaking up a whole system into its basic components, reassembling the components, and blending the entire system in such a manner as to function efficiently (Aguilar, 1973). It does this in an orderly, scientific, continuous, and cyclic optimality search manner of first, defining the objectives, designing alternatives to achieve the objectives, evaluating the alternatives on the basis of some measure of effectiveness, critically questioning the objectives and other underlying assumptions, discovering new alternatives, and reformulating the objectives.

Systems analysis focuses and sharpens the planner's awareness of his objectives by forcing him to explicity specify and quantify them. It then seeks methodologies for predicting the future response of the system that often is not observable or apparent in advance but must be determined from an interaction of physical, social, and economic factors.

Systems analysis establishes procedures for generating a large number of possible solutions and for determining efficient methods to search through them. Optimization techniques are employed to delineate favorable alternatives and suggest strategies for decision making that can be useful in choosing from among possible alternatives (de Neufville and Stafford, 1971).

Thus, the inherent capability for feedback, a firm focus on selection of objectives, and an optimality search constitute the prime advantages of systems analysis over the traditional techniques, essentially based on pure physical theories.

Systems approach, therefore, implies comprehensive confrontation with complex planning and design problems whose solutions can greatly be enhanced using high-speed large capacity computers that greatly reduce the computation burden.

Both systems analysis and the systems analyst most effectively function in specialized areas most frequently associated with the diagnosis, design, evaluation, and treatment of the complex hardware, informational flow and organizational structures that exist to accomplish the specified objectives (Hare, 1967). On this interdisciplinary structure is founded the key utility of systems analysis.

Recently, planners and decision makers in water resources have sought for and obtained meaningful solutions to complex water resources problems employing the techniques of systems analysis. Application of the systems approach is rapidly increasing because:

1) Water projects typically require more or less frequent large-scale physical modifications in time and space.

2) The knowledge and "professional opinion" of many traditional disciplines are concurrently pertinent.

3) Compentent water project managers operating within traditional institutional patterns can develop near-optimal operating strategies by employing the techniques of systems analysis.

4) The size and capital-intensive character of investments in water projects particularly under certain budgetary constraints, large risk and uncertainty factors existing in virtually all water resources projects, indicate the desirability of achieving even small improvement over traditional designs.

5) Systems analysis can be used to obtain meaningful and rational decisions within the complex "web" of greatly diversified and largely incompatible user settings (Bishop, 1974).

6) The design and operation of water resources systems involve

technological and management decisions with long-range frequently irreversible consequences.

3.2 SOME TECHNIQUES OF SYSTEMS ANALYSIS

The techniques of systems are many and varied both in their application and utility. Meta Systems (1971), Gillett (1976), and Aguilar (1973) present partial listings of these techniques.

For any specific problem, a variety of mathematical modeling techniques exists that can be usefully employed to accomplish a solution Deciding which technique is appropriate for a particular problem is rather crucial, as some researchers have rendered their results meaningless by employing the wrong techniques.

In the field of water resources engineering, optimal solutions have frequently been obtained using simulation, mathematical programming, and a combination of both.

3.2.1 SIMULATION

In simulation, the essence of a system is studied without actually distorting its reality by reproducing the behaviors of a system in detail (Maass et al., 1962; Rockwell, 1967). On this basis, large-scale complex problems such as normally found existing in reservoir, river basin and water quality studies are generally simulation suited. This is due to the large masses of input data and outputs often encountered that frequently defy analysis utilizing formal analytical methodologies. Additionally, the availability of large-capacity, high-speed digital computers capable of handling large volumes of data makes it possible to simulate such complex systems.

Manzer and Barnett (1962) narrate the logical steps to follow in formulating and solving a river basin simulation model. Wilson (1972), Dutt (1972), and King (1972) used simulation models in irrigation salinity management and return flow studies.

The popularity of simulation as a modeling technique is attributable in part to its extreme flexibility. Many details and various input combinations can be incorporated into the model. But certain simulation models are sometimes unnecessarily and extensively detailed. Such simulation details may not be important and can, therefore, become cumbersome.

Hall and Dracup (1970) warn that simulation possesses one main difficulty that occurs if a model offers a large number of design alternatives. In a typical trail-and-error iterative search through the alternatives to obtain an optimal solution, a global optimum amy not be obtained. Instead a local optimum may be located. Simulation cannot therefore, yield an instantanous optimum (Maass and Hufscmidt, 1962). Furthermore, the search process associated with simulation is generally time-consuming, expensive, and sometimes completely impossible.

3.2.2 MATHEMATICAL PROGRAMMING

Simulation is actually not an optimization technique but rather a formal tool of sequentially and systematically generating relevant questions and answers concerning the modeled system. However, in utilizing a mathematical programming approach the key objective is optimization achievable by selecting a set of independent variables subject to various imposed constraints (Hadley, 1962, Stark and Nicholls, 1972). Optimality is generally accomplished by applying certain fundamental strategies based on a hill-climbing procedure similar to marginal analysis. This is the path of the linear programming technique. Optimality can also be generated using an enumeration approach that implicitly and exhaustively considers all possible variable combinations. This is the pattern of the dynamic programming technique.

In a study problem, the mathematical programming approach functions in the following manner (Meredith et al., 1973).

1) The real-life essential elements are isolated and structured into a mathematical model so that a solution important to the decision-maker's objectives can be sought. This implies looking at the problem in its entirety.

2) The structure of solutions must be investigated and systematic procedures developed for obtaining the solutions.

3) An important virtue of the mathematical programming approach is its capability, enhanced by the use of computers, to discover optimality under quite complicated circumstances (Dorfman, 1962).

3.2.2.1 LINEAR PROGRAMMING

A linear programming problem encompasses three basic components: a linear objective function, a set of linear constraints, and non-negative restrictions. In attempting to solve a problem utilizing the linear programming approach, both the objective and constraints must be linear functions of continous variables. This therefore, implies that linearity forms the basic assumption that must be met before a convex feasible solution region can be obtained. Convexity implies that no openings exist within the feasible region so that any local optimum must also represent the global optimum.

The general matrix configuation of a linear programming model can be found in most standard systems analysis texts such as de Neufville and Stafford (1971), Stark and Nicholls (1972), and Meredith et al., (1973). Once the problem has been structured in the matrix format, the solution can readily be obtained using pre-packaged linear programming computer programs.

Major drawbacks in using linear programming in a real-life situation are that the variabilities and inaccuracies of input data employed in generating the coefficient matrix and also the fact that the factors operating in natural systems are seldom linear.

Post-optimal analysis through sensitivity analysis reveals optimality response as a function of certain variable input data. Most computer linear programming output contains duality that is an important concept which improves the understanding and utility of linear programming. The concepts of shadow prices and opportunity costs that are important components in sensitivity analysis, are based on the theory of duality (de Neufville and Stafford, 1971, Stark and Nicholls, 1972).

3.2.2.2 NON-LINEAR PROGRAMMING

Since both the objective and constraints of a linear programming problem must be linear functions, the measure of effectiveness and resource use can only be proportional to each level of activity. Therefore, techniques other than linear programming must be used to solve nonlinear problems which typically lack proportionality between components factors.

Most of the factors operating in irrigation systems usually generate non-linear functions. Therefore, applying the methodology of linear programming in solving irrigation systems problems could prove a harmful oversimplification of a truly complex problem. However, Stark and Nicholls (1972) suggest an approach of roughly approximating an arc with small chords and then obtaining a solution in a stepwise-linearization manner.

Non-linear models are generally complex to formulate and solve. Wolfe (1970) categorized non-linear programming models according to their degree of complexity in the manner:

1) Separable programming models where each function in the model is the sum of functions of a single variable. This model permits replacement of non-linear functions with additive piece-wise linear functions. Separable programming does not necessarily lead to a global optimum (Hadley, 1964).

2) Quadratic programming models having linear constraints and convex quadratic objective function of the form:

$$A(X) = \Sigma_i C_i X_i + \Sigma_i \Sigma_j d_{ij} X_i X_j \qquad (3\text{-}1)$$

Solutions to this form of model have been obtained at a cost of greatly enlarged computations (Wagner, 1966; Wolfe, 1963).

3) Models having linear constraints and a non-linear differentiable objective function.

4) Models whose constraint and objective functions are non-linear but differentiable.

5) Models whose constraint and objective functions are non-linear and non-differentiable and thus are not readily calculable.

The task of finding and selecting the best technique of obtaining a non-linear model solution is frequently very problematic. Bayer (1974) suggests examining existing coded algorithms to determine the most efficient for the particular model under consideration. The next approach is to utilize published experiences of other researchers as guides in selecting adequate algorithms. Since none of the existing algorithmic methods can claim significant superiority over others, few packaged algorithms have been developed for accomplishing solutions to non-linear problems.

3.2.3 DYNAMIC PROGRAMMING

In using dynamic programming, most of the limitations of linear programming can be completely eliminated. Previously assumed unsolvable problems have found solutions using dynamic programming (Roberts, 1964). This has been possible because dynamic programming can find the optimum even when the feasible region is not convex. In addition, solutions are not limited to continous variables alone, and both the objective and constraints may be non-linear functions.

A dynamic programming solution is obtained through an enumerative step-wise search through a set of all possible combinations of the variables that comprise the objective function. This iterative search finally leads to an optimal solution. Dynamic programming is, therefore, easily applicable to stage or sequential problems. Upon this basis lies its utility in solving allocation problems (Ackoff and Sasieni, 1968; and Beveridge and Schechter,1970). However, if a problem involves a large number of constraints, use of the dynamic programming approach is usually not advised.

A very large complex combinatorial problem can sometimes be decomposed into many small problems containing only few variables per stage.

In this manner, decomposition first proposed by Dantzig and Wolfe (1961), can greatly reduce the magnitude of computation.

Dynamic programming is more of a point of view or philosophy than it is a rigorous mathematical tool (Mickle 1972). Its philosophy is based on the principle of optimality developed by Bellman (1957) which states that:

"An optimal policy has the property that whatever the initial state and decision are, the remaining decisions must constitute an optimal policy with regard to the state." Busch (1974) utilized this principle to develop a pruning concept that systematically eliminated less plausible and non-optimal combinations that are encountered as the process of iteration sequentially progressed.

Since dynamic programming is actually an optimization approach rather than an algorithm as in linear programming, a systems designer can rarely find suitable prepackaged computer routines. Therefore, for each problem under consideration, a separate routine must be developed. In other words, every dynamic programming problem is unique and must, therefore, be structured to fit the existing problem or situation under consideration.

3.3 APPLICATIONS OF SYSTEMS METHODOLOGY TO IRRIGATION AND WATER RESOURCES SYSTEMS

In most developed nations, particuarly the United States, agriculture and irrigation specifically, are becoming an increasingly complex arena where man, machine, money, biology, and environment are regulary interacting and engaged in producing food and fiber (Stewart, 1967). Those tools of systems analysis that have proven powerful and competent in water resources and business management decisions can be usefully employed in creating more powerful, efficient, and economic agricultural production strategies.

Recently, irrigation planners and designers have used optimization techniques for solving certain complex irrigation systems problems. The optimization techniques employed are many and varied, and the problems they have been applied to, are also many and varied. They range in complexity from specifying individual components of a small irrigation system to the operation and management of large multipurpose water resources systems. Hutton (1965), Agrawal and Heady (1972), and Smith(1973) reviewed the trends and systems applications to agricultural decision problems. In irrigation systems managment, decisions are regulary made concerning water allocation between projects and crops within projects. Under limiting water supply conditions, an optimal water allocation may be highly desirable in ensuring efficient and equitable water use.

In their water allocation studies, Van Deman et al., (1976) Clyde et al., (1971), Champion and Glaser (1967), Castle and Lindeborg (1960) used a linear programming approach, while Buras et al., (1973), Hall and Buras (1961), Dudley et al., (1976), Trava et al., (1976), Howell and Hiler (1975), and Windsor and Chow (1971), used either linear programming, dynamic programming, simulation, or their various combinations. Milligan (1971) considered water allocation partly on water balance concepts, while Anderson (1972) linearized his developed non-linear functions to optimize returns for the Jordan River Basin in Utah.

Physical and economic problems associated with the conjunctive operation of surface and groundwater supplies may require investigations using systems analysis techniques. Buras (1963), Rogers and Smith (1970), Bear and Levin (1966, 1967), Aron (1969), Burt (1964), Blanchard (1964), Milligan (1970), and MeConnen and Menon (1968), utilizing linear programming, dynamic programming, or their combination, optimized surface and groundwater systems.

Young and Bredehoeft (1972) modelled the inter-relationships between the river and aquifer systems, while Spofford (1965) employed a non-linear programming approach to allocate surface and groundwater quantities between irrigated areas. Dracup (1966) also examined multiple water supply and use functions, using a parametric linear programming approach.

The life line of an irrigation system includes the water supply or source system which usually includes the characteristically dendritic distribution system, and application system(s). Studies concerning the structure and efficient operation of either the complete line or separate systems components have been conducted and least cost functions have been developed.

Busch (1974) developed a rather sophisticated approach using dynamic and linear programming that can be applied in selecting and arranging irrigation systems components based on a least-cost configuration. While Huszar et al., (1969) used a simulation model for duplicate canal system consolidation plans, Deb and Sarkar (1971), Mandry (1967), and Horn (1967) studied the selection of economic pipe sizes for a distribution system based on pressure or border strip width factors. These studies used non-linear optimization processes.

In irrigation systems studies, crop response functions may be viewed as a link between the hydrologic and economic components (Packer et al., 1969). Some investigators have optimized irrigation systems operation considering crop response functions. Stewart et al., (1974), Ahmed et al., (1976), Jensen and Wright (1976), Flinn and Musgrave (1967), and Young and Martin (1967) modelled crop response to irrigation water application, using statistical simulation approaches. These studies displayed certain complex interactions existing between soil, water, and crop factors, making it rather difficult to isolate water supply as a single factor affecting crop production.

While Gisser (1970) applied a parametric linear programming approach in investigating agricultural demand as a function of imported water costs, Lindeborg (1970), and Hartman and Whittelsey (1970) were concerned with determining the value of water and farm adjustments under variable water supply using the approach of linear programming in conjunction with marginal analysis.

Other relevant studies within irrigation optimization context include Wensink et al., (1973), Keller et al., (1972), Schatz and Michalson (1975), Gotsch (1966), Corey (1969), Martin et al., (1969), Strong (1960), Kleinman (1972), Conklin and Schmisseur (1973), and Mann et al., (1968).

The major drawback of previous studies is in their failure to explicity incorporate and adequately consider those risk and uncertainty factors frequently known to plague irrigation systems planning, design, and development. Most of these studies have erroneously assumed a steady state or static deterministic setting. Some models are also very detailed and complex, often resulting in loss of communication between the modeller and his clients. This frequently limits the application or utility of the models, particularly in developing nations.

CHAPTER IV
TRADITIONAL RISK AND UNCERTAINTY PROGRAMMING TECHNIQUES

4.1 RISKS AND UNCERTAINTIES IN AGRICULTURAL AND IRRIGATION SYSTEMS

Irrigation systems planning, design, and management inherently encompass a hierarchy of decision making processes in time and space. Most of these decisions must be made in the face of risks and uncertainty. Uncertainties stem largely from externally induced factors resulting from changing policies, technological innovations, social transformations, institutional standards and requirements, dynamic economic conditions, randomness in nature, and ignorance about nature (Davis, 1968).

Hildreth (1957) has described some of the decision problems involving uncertainty in farm planning. Just (1974), Wharton (1968), and Boussard (1969) pointed out those risks and uncertainty factors confronting the subsistent farmer. Dillon and Heady (1961) viewed decision making under uncertainty as a game of nature.

In the design of irrigation systems components, uncertainties exist due to sparse and non-homogenous data. Also, selection of certain critical design parameters, particularly irrigation efficiency, hydrologic inputs and crop water requirements, most of which are inherently stochastic, is susceptible to uncertainty.

Hydrologic inputs such as streamflows and precipitation are in reality stochastic, that is, their values are subject to spatial and time variability (Chow and Kareliotis, 1970, Todorovic and Yuvjevick, 1969). Streamflows are a variable and erratic paramter dependent on precipitation and resultant hydrologic conditions present in a river basin.

In developing nations where data are frequently either sparse or completely lacking, data transfers from nations such as United States are very common. Such transfers are obviously plagued with uncertainty.

Crop water requirement is a complex function of temperature, humidity, radiation, day length and wind velocity factors; all of which are subject to large variabilities and hence uncertain (Dudley, 1972).

Irrigation technique, amount and timing involve decisions under uncertainty that cannot be eliminated using even the scientific check book-type computerized irrigation scheduling services. The scheduling services themselves are not adequately immune to some degrees of uncertainty, as the approach is an embodiment of soil science, agronomy, meteorology and engineering components; each component bearing considerable uncertainty elements.

Thus, those models that have incorporated only deterministic inputs have erroneously assumed that the values of design parameters are both known and fixed. In reality, they are neither constant nor known with complete certainty, but are in fact random variables.

4.2 TRADITIONAL APPROACH TO PROGRAMMING UNDER RISK AND UNCERTAINTY

The existence of uncertainties in decision-making processes involving irrigation planning, design, and development is well established, and attempting to completely eliminate them is an almost impossible task. Decisions must, therefore, be made in the face of uncertainty. The key question is then how to adequately and quantitatively account for uncertainty.

Most irrigation systems designers have frequently either simply assumed away all aspects of uncertainty by incorporating estimation techniques with conservative tolerance margins or attempted to contain uncertainty by involving the so-called engineering judgment that permits them to employ arbitrary safety factors.

Many workers have proposed various techniques of handling uncertainty. James and Lee (1971) suggest attaching a value to risk components. Allowance for risk would then be provided by deducting the risk value from net returns to a project or by adding it to the project costs. The weakness of this approach clearly rests in maintaining consistency in subjectively assigning values to risk factors.

For uncertainty resulting from entirely social, political, physical, and environmental factors, Friend and Jessop (1969) simply suggest collection of more data and improvement of communication among agencies. This approach obviously implies additional costs.

In economics, certain rather vague and impractical concepts have been developed in traditionally solving problems involving uncertainty. The certainty equivalent, the gambler's indifference map and the risk discounting techniques are all too vague to be competent practical tools for treating uncertainty.

In irrigation systems planning, design, and development, optimal strategies devised utilizing deterministic models require entirely deterministic inputs of the physcial components and complete certainty of the state of nature. Since irrigation systems function in a dynamic and uncertain environment where postulated certainty conditions do vary, flexibility and adaptability of optimality can be shortlived unless tested in a manner reflecting uncertainty through a sensitivity analysis (Amir et al., 1976; Wiener 1973).

For a sensitivity analysis to be effective, both optimistic and pessimistic values must be used and a sufficiently large series of iterations performed in order to locate optimality. This approach can be both time and money intensive. Besides, such established optimality goals based on deterministic criteria are either inadequate or too simplistic to cope with randomness of nature.

The probablistic nature of the critical design parameters characterising irrigation systems must, therefore, be recognized and considered in decision-making processes.

Several optimization schemes to solve irrigation systems planning problems under risk and uncertainty have been formulated. The major approaches used are stochastic programming with recourse and chance-constrained programming.

4.2.1 STOCHASTIC PROGRAMMING WITH RECOURSE

This technique involves first, partitioning the problem into two or more stages. In the first stage, prior to the occurrence of any stochastic events, certain decision variables are selected. In the second stage, the stochastic events occur, and some constraints are violated. The decision maker can still meet the violated constraints by making a series of second stage decisions that may involve a penalty. The linear formulation of this approach may be written as follows:

$$\begin{aligned} &\text{Max } Z(x) = C^1x - E\,(\text{Min } q^1y); \\ &\text{Subject to } Ax = b; \qquad\qquad (4\text{-}1) \\ &\qquad Tx + Wy = \xi;\; x \geq 0,\; y \geq 0 \end{aligned}$$

in which C^1 = a vector of prices; b = a vector of resource availabilities; A = a matrix of technological coefficients; x = a vector of decision variables; q^1 = a vector of penalties incurred due to deviations from the target; T and W = matrices of technological coefficients;

ξ = a vector of stochastic elements; y = a vector of second stage decision variables. The parameters C, P, T, W, and ξ may contain stochastic elements.

The solution strategy of the programming involves choosing x (to satisfy Ax = b and $x \geq 0$) such that when the stochastic variables are observed, y can be chosen to satisfy $y \geq 0$ and $Wy = \xi - Tx$, and to maximize the difference between the expected first stage benefits and second stage costs (Smith, 1973).

The limitation of this approach involves the difficult tasks in obtaining the requisite loss functions for crops under certain moisture stress regimes especially where little research has been conducted. Another limitation is that the technique's utility is strictly confined to a unidimensional objective function and optimizing the expected value only. However, stochastic programming with recourse provides a format for incorporating into a model crop water response functions and other technical data (Smith, 1973).

4.2.2 CHANCE - CONSTRAINED PROGRAMMING

This approach involves allowing constraint violations a certain proportion of the time and ignoring their explicit costs. A formulation of this approach may be written as follows:

$$\text{Max } f(c^1x);$$

$$\text{subject to } \Pr(Ax \leq b) \geq \underline{\alpha};\ x \geq 0 \qquad (4\text{-}2)$$

in which

Pr = the probability operator

α = a vector of probability measures

The decision variables, x, are selected by a rule depending on the stochastic variables, A, b, and c; thus x = D(A, b, c). The form of D is frequently specified in advance as linear. The function $f(c^1x)$ is usually in the form of an expected value that would be maximized.

The main attraction of this programming techniques is that computational methods exist to solve the deterministic equivalent problem resulting from the chance - constrained problem formulation (Smith, 1973).

4.2.3 STOCHASTIC PROGRAMMING APPLICATIONS TO IRRIGATION PROBLEMS UNDER UNCERTAINTY

Different forms of stochastic programming techniques exist that have been applied to various irrigation decision problems under uncertainty. These problems include reservior operations within an irrigation context, irrigation water supply and allocation, crop water demands and other related problems.

In reservior operation strategies specifically relating irrigation demand functions, Anderson (1968), Anderson and Maass (1971), Butcher (1971), and Hall et al., (1968) studied stochastic inflows to the reservior but assumed nonstochastic crop water demands. Thomas and Watermeyers (1962) examined associated problems. Using dynamic programming, Dudley et al., (1971) investigated both stochastic inflows to a reservoir and stochastic crop water requirements.

Eastman and ReVille (1972), Loucks and Detrick (1967), and Loucks and Falkson (1970) developed a variety of stochastic models featuring chance - constrained techniques, stochastic linear programming, policy iteration methodology and their combinations. This work focused on optimal operation strategies for multiple-function reservoirs.

Recognizing the inherent variability of irrigation water supply and crop water requirements, Hall and Buras (1961) studied stochastic water demand, but assumed deterministic water supply. While Conner et al., (1971) and Moore (1972), using simulation, stochastic linear programming, and response surface techniques, considered stochastic water supply, Dudley et al., (1971) employed a two-state variable stochastic dynamic programming approach and allocated a fixed water supply under stochastically varying rainfall and crop use. In another work, however, Dudley et al., (1972) investigated both stochastic water supply and crop demand functions.

Some investigators have based irrigation water allocation decisions on land and crop factors. While Burt and Stauber (1971) allocated priced water to a single crop, DeLucia (1969) using a stochastic dynamic programming approach, additionally accounted for economic and hydrologic variabilities. Huang et al., (1975) utilizing stochastic linear programming with recourse, optimized water allocation under a multiple cropping setting.

Onigkeit et al., (1969) optimized land and water allocation within an irrigated area, using a combination of stochastic programming, linear programming and dynamic programming. While the stochastic model generated surface reservoir capacities, the dynamic programming generated reservoir - irrigated area combinations and the linear programming unit optimized land and water allocation.

Zusman and Amiad (1965) and Halter and Dean (1965), utilizing simulation techniques, investigated weather and crop price variabilities. Yaron and Horowitz (1972) used a sequential programming approach in a manner proposed by Dantzig (1963). Chen (1973) and How and Harrell (1968) used a quadratic programming approach. Chen (1973) was concerned with least-cost feed functions, while How and Harell (1968) considered farm management strategies. Amir (1972) using a probablistic linear programming approach, and Rae (1971) employing stochastic sequential programming considered farm management strategies. In another work, Amir et al., (1976) constructed a combination linear programming and simulation queuing theory based model that could be activited by emergency inputs.

Nearly all studies concerning stochastic crop water demand functions have assumed a constant irrigation efficiency regime. In reality, irrigation efficiency is neither constant nor even known with complete certainty.

CHAPTER V

STATEMENT OF THE PROBLEM AND THE STUDY OBJECTIVES

5.1 STATEMENT OF THE PROBLEM

One of the most crucial and often encountered parameters in irrigation systems planning and management is irrigation efficiency. This parameter has many definitions in published research literature. Willardson (1972) showed that more than twenty definitions are presently in existence.

The many definitions of irrigation efficiency clearly demonstrate and reinforce the concept that the phenomenon is a complex function that is difficult to define and not completely understood. Willardson (1972) and Thompson (1974) stated that it is a complex function of many interacting variables including the irrigation system's inherent characteristics, management, labor input, institutional factors, and water costs. Soil, crop, timing, and irrigation quantities, most of which are subject to large variabilities in time and space also greatly influence irrigation efficiency.

Researchers have frequently misunderstood and consequently misapplied irrigation efficiency concepts. An over-indulgence on improving irrigation efficiency may generate new problems in reaching and achieving national water resources goals and objectives (Jensen, 1977), as inefficient irrigation systems may have an indirect benefit of recharging an aquifer system.

Jensen (1975) has defined irrigation efficiency as the ratio of water used in evapotranspiration by crops or an irrigated field, farm, or project to the water diverted or pumped from a river system or other natural source for that purpose. This implies that irrigation efficiency is a parameter important to the design engineer and irrigation decision maker, in partially quantifying the total irrigation water utilization and in determining the proper sizing of irrigation systems components.

Valenzuela (1974) warned that rather than spend excessive time and money defining and redefining evapotranspiration, irrigation systems researchers should invest that time and effort in specifying and directly quantifying the obvious impact of the deterministic irrigation efficiency assumptions on optimal strategies. A quick check showed that the errors of fixed irrigation efficiency were usually more critical than the normal errors inherent in the uncertain climatic parameters associated with evapotranspiration equations.

The clear agrument is that this critical parameter is rarely adequately quantified by researchers. At the time of design, the actual value is never known with complete certainty. In fact, the value is usually experimentally determined after the irrigation system is in-place. Even after the system is built, irrigation efficiency is subject to large variabilities in time, place, and personnel.

Almost every design engineer or irrigation decision maker has traditionally and arbitrarily selected a certainty value for irrigation efficiency relying on the so-called engineering judgement developed from experiences with existing irrigation systems. This implies that almost all in place irrigation systems components have been undersized, rightly sized, or over-sized depending on the choice of the parameter value.

An oversized system could possibly lead to escalated overall project cost, while an undersized system could lead to crop loss due to the incapability of the systems components in supplying water adequately both in time and in quantity. Many optimal designs that have been developed using a deterministic irrigation efficiency parameter can in fact prove nonoptimal under variable irrigation efficiency regimes.

No published literature has been found that explicitly incorporates irrigation efficiency as a "non-steady state" parameter. It is considered of vital importance that optimal irrigation systems design should recognize and completely consider the full impact on irrigation management strategies due to the uncertainty and variability associated with irrigation efficiency and hydrologic phenomena.

5.2 THE STUDY OBJECTIVES

The main objective of this study will be the development of a methodology for optimal decision-making relating the management of an irrigation system to various hydrologic and irrigation efficiency regimes.

Specifically, the study objectives are:

1) To develop a model that would be structured in a form both suitable and powerful in selecting that optimum land area to be seasonally committed to irrigation.

2) To directly and explicity consider in the model the largely unreliable and unpredictable hydrologic and irrigation efficiency parameters.

3) To test the capability of the developed model by applying it to a selected irrigation district.

4) To demonstrate that the model could be a powerful tool for optimal irrigation management decision-making for developing nations.

That is, the developed model should be reasonably efficient in time, effort, and money inputs.

5) To conduct a post optimal investigation testing the stability of optimality to variabilities in the model parameters.

CHAPTER VI

THE DECISION THEORY METHODOLOGY AND MODEL DEVELOPMENT

6.1 CONCEPTS OF DECISION THEORY

The reason irrigation efficiency is not treated as a stochastic design and management input by most workers is that traditional methodologies for solving irrigation design problems under risk are either too vague to yield realistic solutions or too inflexible to accommodate and adequately account for the purely subjective approach that must accompany irrigation design decisions under an uncertain irrigation efficiency regime.

Recently, a new theory of applied probability and statistics called statistical decision theory has evolved and been employed in agricultural decisions under uncertainty. This theory provides a powerful mathematical tool that formalizes decision making under uncertainty. The technique is adaptable to both the use of probability theory and to situations where subjective and objective inputs must be considered in optimization. The complexity of irrigation systems design, planning and development creates such situations.

Furthermore, the decision theory methodology incorporates facilities and flexibility through Baye's Theory to revise or update subjectively determined prior probability density functions as new information through experimentation becomes available (Vicens et al., 1975).

Although the true value of the irrigation efficiency parameter is never known with complete certainty, irrigation systems designers and management decision makers have usually assigned deterministic values to it. Realistically, the probability density function of the occurrence of the unknown state of the nature of the phenomenon should be determined by obtaining and statistically analyzing a large sample of irrigation efficiency data. However, where a large sample is unavailable and expensive to obtain, subjective estimates based on judgement, experience, sound logical thinking, and knowledge of the behavior characteristics of common probability distribution functions are pertinent.

After an irrigation system is built and some irrigation efficiency experiments conducted, the subjectively derived prior probability density function can then be updated and refined using Bayesian methodology. With refined data, an optimal irrigation management strategy can be seasonally generated particularly prior to any cropping event.

Upon this seemingly powerful function of incorporating new information and research findings, hinges the key rationale for using the Bayesian decision theory optimization technique.

Many workers have employed the methodology in their studies. Igwe (1976) investigated hydrologic stochasticity, while Stewart et al., (1974) considered uncertain evapotranspiration. Weng Rong (1973), Eidman and Carter (1967), Carlson (1970), Bullock and Logan (1970), and Anderson et al., (1971) have each used decision theory approach in specific agricultural problems involving uncertainty.

6.2 TYPES OF DECISION AND FUNDMENTAL STEPS FOR DECISION MAKING UNDER UNCERTAINTY

A typical decision making process can exist under certainty, risk, and uncertainty. If the resultant outcome or consequence of a decision alternative can be known in advance and with complete reliability, decision is said to be made under certainty. This is the type of decision reached using marginal analysis, calculus and input-output concepts. However, if a chance-outcome is envisaged, the probability of it occurring may or may not be known. If the probability is known, the decision is said to be made under risk. Otherwise, decision is made under uncertainty.

A typical decision making process under uncertainty (Raiffa and Schalaifer, 1960) can be outlined as follows:

1) Space terminal acts: A=(a). The decision maker wishes to select a single act, a, from an A domain of potential acts.

2) State space: $\theta = (\Theta)$. The decision maker believes that the consequences of adopting a terminal act, a, depends on some state of nature which cannot be predicted with complete certainty. Each potential state of nature, Θ, is embedded in a θ domain.

3) Sample space: Z = (z). Each terminal act and state of nature is associated with a potential outcome, z.

4) Utility evaluation: U(, , ,): $U(Z \times A \times \theta)$. To be logically consistent with his basic preference concerning outcomes, the decision maker assigns a utility $U(Z,a,\theta)$ for taking an action, a, under a state of nature, Θ, and expected terminal act, z.

Utility functions do not represent real monetary outcomes (Schlaifer, 1961). They represent the intrinsic worth of a monetary outcome that truely reflects a person's natural aversion to risk. Thus, they portray an inseparable mixture of human response or attitude toward risk, profit, and loss.

A decision problem under uncertainty can thus be visualized as follows: a choice must be made among a number of alternative courses of action. The practical consequences or terminal outcomes of adopting any particular action will depend not only on the choice made but also on other critical parameters represented by the states of nature which are uncertain.

In decision analysis, the possible decision alternatives are usually diagrammed along with chance events and the terminal outcomes. This formulation can be displayed graphically as a decision tree shown in Figure 6-1. It can be observed that each action - states combination yields a matrix of terminal payoffs. In order to be consistent in selecting among the various alternatives or actions and in reflecting the decision maker's basic reaction toward risk regarding the subjective assignment of probability density functions to the unknown states, the terminal outcomes must be transformed to utilities. The transformation can be achieved by generating and using the decision maker's utility function. After the transformation process, the utilities are summed over the specified states of nature for that action. The optimal strategy is to select that action or that alternative yielding the greatest total expected utilities. The components of a decision making process are shown in Figure 6-2.

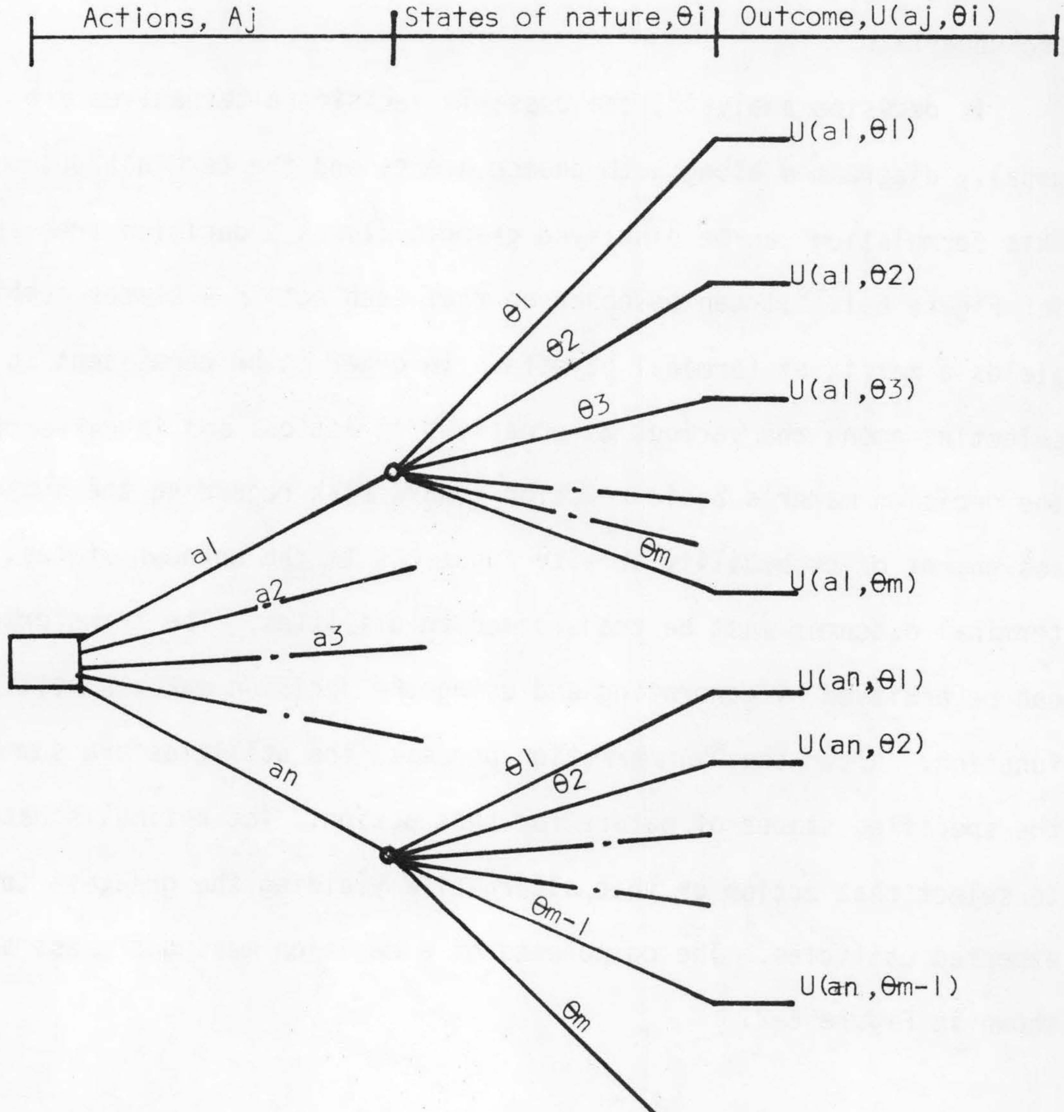


Fig.6-1 Decision Tree for Discrete - state Space.

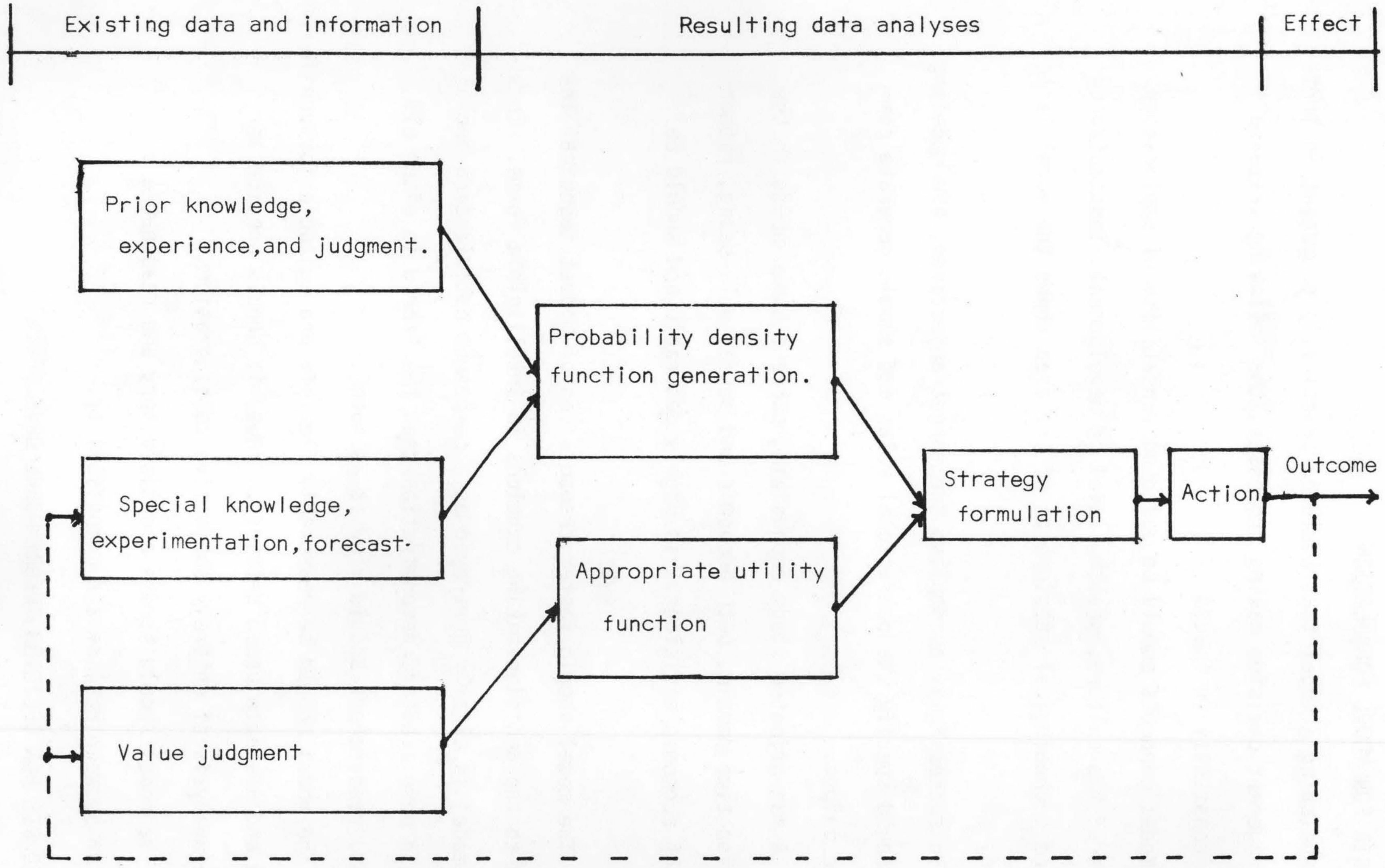


Fig.6-2 Components of Decision Making Process.

6.3 CRITERIA FOR MODEL FORMULATION

In developing a model that would be practically competent in irrigation management decision making processes, the following criteria should be constantly in focus:

1) Model concepts should be based on versatility of application regardless of the culture, wealth, level of development, institutional setting and technological attainments of the area where the model is to be applied.

2) To successfully accomplish the target objectives, the modeling process should specify the operational rules and should generate comprehensive output.

3) A man-oriented study emphasizing current human needs in the optimization time domain, both economic and social well-being, rather than strict economic efficiency, is highly desirable and should be pursued.

4) The model should foster transmission of modest technical information to the decision-making echelons in intelligible forms. This way, the model is clearly portrayed as a competent optimization tool rather than mere academic demonstration that the "world is after all complex and researchers should view it as such".

5) The model should be reasonably flexible and suitable for use in both data and non-data based settings. Thus, it should provide an objective analysis of entirely subjective considerations.

6) The model should strike a satisfactory and reasonable equilibrium between realism and computability.

6.4 PROCEDURES FOR DECISION THEORY MODEL DEVELOPMENT

In developing a decision theory stochastic optimization model, the following steps should be adopted:

1) define the decision or decisions to be made

2) develop the criterial objective function

3) define and represent the uncertainty of the different states of nature as probability density functions, pdf

4) describe the model input functions

5) develop the decision strategy by:

a) computing the expected monetary value, EMV, or the expected utility, EU. The expected monetary value, EMV, is the product of the terminal monetary payoff and the associated probability of the considered unknown state of nature. This is given by:

$$\text{EMV} = \text{dollars} \times \text{probability} \qquad (6\text{-}1)$$

The expected utility, EU, is the product of the terminal monetary payoff that has first been transformed to its utility equivalent and the associated probability of the considered unknown state of nature. This is given by:

$$\text{EU} = \text{utility} \times \text{probability} \qquad (6\text{-}2)$$

b) choosing that alternative that maximizes EMV and/or EU.

6) Revise the optimal policy by incorporating new data obtainable from experimentation or forecasts using Bayesian strategy.

6.4.1 DEFINITION OF DECISION ALTERNATIVES

In this process, the irrigator or the irrigation systems designer must select a single act, a, from an A domain of potential acts.

Kleinman (1972) points out that land and water are the most fixed factors limiting irrigation systems development. When land is more limiting, the unit of water requirement determines how much of available water supply would actually be used. However, once an irrigator is faced with sporadic water shortages, his reactions could be many and varied.

One possible reaction is a decision to partially irrigate the crops in which per acre quantity of applied water would be restricted so that the limited supply could then be spread over a larger area than would have been possible under an unlimited water supply regime. Using this decision process requires an input of crop response as a function of applied irrigation water particularly under limited water availability.

Another possible response to water shortage is that some marginal farmers could decide to depart the farming enterprise. This would imply a rather expensive and vital decision.

Other irrigators might possibly try to substitute water saving systems such as sprinkler, trickle, pipelines, and concrete ditches or replace marginally profitable crops with more profitable, and more productive crops, or even rotate the crops. Thompson (1974) suggested temporarily improving water use efficiency and revising the cropping pattern.

Certain irrigators are most likely to react rather quickly, in advance of the irrigation season, by deciding on the optimum quantity of land to be committed to irrigation under stochastic hydrologic and irrigation efficiency regimes. Based upon this belief, the model will be developed to select that optimum land area, A_j, to be seasonally committed to irrigation under highly unreliable and largely unpredictable hydrologic events and uncertain irrigation efficiency. Any stochastic water supply must be used to uniformly irrigate the entire considered land.

6.4.2 CRITERIAL OBJECTIVE FUNCTION

In the design of an optimal irrigation system, there must always exist some measure of effectiveness or efficiency which one must seek to optimize subject to certain fundamental requirements or constraints. While the scale of efficiency could be derived entirely as a function of the system properties, it is often traditionally a measure of economic efficiency. For most cases, the criterial objective function seeks to maximize the present value of the net project.

However, if the project involves appreciable elements of uncertainty such as often encountered in irrigation projects, maximization of strictly monetary function is not customary (Lin et al., 1974). Usually the objective function to maximize is either the expected monetary value, EMV, or the expected utility, EU.

Since farmers in general have a real aversion to risk and uncertainty, a realistic criterial objective function should be maximization of the intrinsic worth of the monetary payoff function, that is, the expected utility of outcomes (Davidson and Mighell 1963; Dillon and Anderson, 1971; and Smith, 1973). This criterion is considered superior to the maximization of expected monetary value, EMV, because a decision problem under uncertainty using the expected utility criterion yields rather conservative but consistent results that nearly reflect the decision-maker's choice among risky alternative actions (Luce and Raiffa, 1957; Officer and Halter, 1968; Savage, 1954; and Schlaifer, 1961; Chernoff and Moses, 1959 and Morris, 1964).

Sometimes, certain problems arise regarding whether to adopt maximization of the expected monetary value, EMV or expected utility, EU.

Situations do exist where maximization of expected monetary value, EMV is materially equivalent to maximization of expected utility, EU.

Consider an example where there are two alternative actions, Ai, and two states of nature, θi, with equal probabilities of occurence for each alternative action (Figure 6-3).

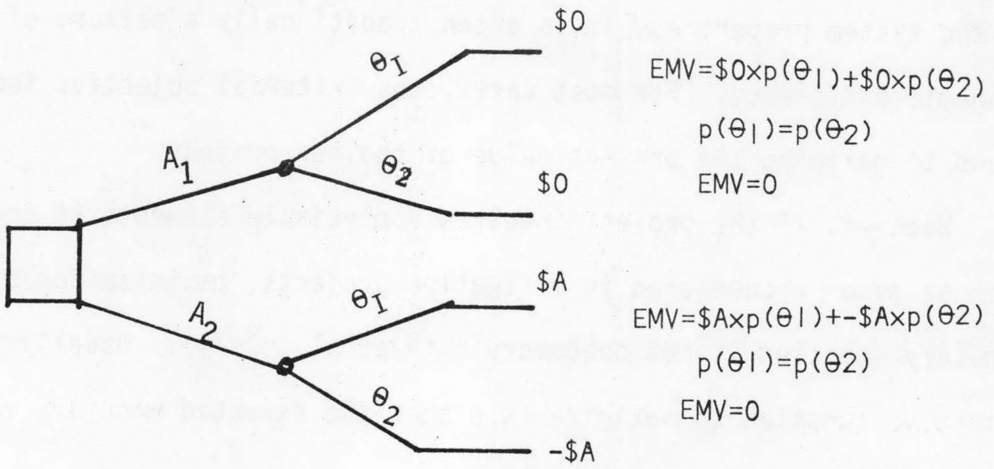


Figure 6-3 Decision demonstration considering EMV criterion

If the alternative action, A_1, has monetary payoffs of $0 for θ_1 state, and $0 for θ_2 state; and the alternative action, A_2, has monetary payoffs of $A for θ_1 state, and -$A for θ_2 state, then the expected monetary value, EMV, for each alternative action would become zero. In this situation, the decision-maker would be indifferent between actions A_1 and A_2 using the expected monetary value as the criterial objective function. However, most people would not be indifferent if the terminal outcomes $A were large sums of money.

Other circumstances exist where maximization of expected monetary value is adequate basis for choosing between alternative actions (Dorfman, 1962). Such cases are found when all the alternatives have roughly similarly deviating outcomes or when a decision-maker functions in a manner typical of an insurance company, that is, every dollar is equally valuable. Dorfman (1962) points out also that if the various monetary outcomes are properly evaluated, if the choice between alternatives must be repeatedly made, and if utility is linear in dollars, then expected monetary value, EMV, would be an adequate measure of desirability and the criterion upon which to base decisions.

As selection of either criterion, EMV or EU, could influence optimal strategy, both objective functions will be incorporated in the model to be developed to evaluate and demonstrate their differences.

6.4.3 SPECIFICATION AND DEVELOPMENT OF PROBABILITY DENSITY FUNCTIONS

The basis of statistical decision theory is that decision making is to be undertaken under uncertainty. Some of the factors generating uncertainties in irrigation systems design include the following:

1) uncertainty and variability in time and space in irrigation efficiency values

2) hydrologic variability both in time and space existing within the irrigation growing season

3) time and space variability in crop water requirements

4) variability in crop response as a function of water applications

5) spatial and time variability of crop prices resulting in income variability

These specified uncertainty sources describe some of the various states of nature than can exist to influence optimal irrigation systems design efforts. In practice, it is seldom possible and hardly reasonable to ensure that all these various states are completely incorporated and fully evaluated in a model. To attempt to achieve this would greatly enlarge the problem and the computations. In the model developed, only the hydrologic and irrigation efficiency factors are included. The impact on optimality due to variabilities in other input parameters will be investigated in the post optimal analyses.

Two approaches are commonly considered in determining the probability density functions. The first one, the objective approach, is usually derived from the relative frequency in a long-run series of repeated events. This approach is suitable for analysis of hydrologic events such as streamflow and precipitation, and crop irrigation water use, where historic data are usually plentiful and long term.

In the second approach, probability assignment must be determined subjectively using the judgment and experience of experts knowledgeable in the considered phenomenon. Such probability density functions determined either objectively or subjectively are called prior probability density functions or no-data probability density functions.

Subjective probabilities are assigned when decision making processes occur in the absence of available recorded series of repeated events upon which to base the computation of the objective probabilities. This is frequently the situation in many developing nations where data are either sparse or largely unavailable. Sometimes, even where data are very plentiful, certain long term observed data are characteristically not suited for analysis by the relative frequency techniques, making it increasingly difficult to obtain a probability density function, pdf.

Tribus (1969) found no real difference between objective and subjective probabilities since a probability determination is essentially a numerical encoding of a state of knowledge of events. Subjective probabilities are mostly intelligent guesses representing an individual's views (Thierauf and Klekamp, 1975). Savage (1954) states that it incorporates all the universally acceptable criteria for rationality in judgment. Although subjective probability determination appears to be somewhat questionable and completely devoid of the rigors of mathematical analysis, it is better than completely ignoring the probability of the occurrence of the different states of nature. There are cases, if no good reason exists to believe that any one event is more likely to occur than any other, there would similarly exist no reason to assume that the events would not occur with the same probability. This concept, of the principle of insufficient reason provides the basis for the Laplace Criterion of assigning equal probabilities to the occurrence of each state of nature (Richard and Greenlaw, 1972).

In this study, the probability density function $P(\Theta i)$ of the occurrence of the unknown state of nature of streamflow, Θi, is determined using a relative frequency analysis. The prior probability density function $P(\Theta_k)$ of the occurrence of the unknown state of nature of irrigation efficiency, Θk, is partially determined by subjective techniques assisted by a rational selection of an adequate respresentative probability distribution function.

6.4.4 MODEL INPUT FUNCTIONS

Prior to the formulation of the decision theory model, certain input functions must first be generated. They include the irrigation crop production cost, crop response, and utility functions.

6.4.4.1 CROP RESPONSE FUNCTION

In order for the model to be accurate and reliable, a function for each typical irrigated crop must be developed and used to relate specific crop response to varying amounts of applied irrigation water. Numerous research efforts have been made by such investigators as Musick et al., (1963), Jensen and Sletten (1965b), Soriano and Ginza (1975), Stewart and Hagan (1972), Keller et al., (1972), Mutz (1976), Yaron (1971), Otterby and DeBoer (1976), and Wilson (1969), to develop crop response functions. Despite their efforts, none of the presently developed functions is found in a shape suitable for incorporation into a decision theory optimization model. The development of suitable crop functions would involve intensive and exhaustive research efforts that could require large investments in time and money, and may lead to delay in model building and planning implementation.

As crop response is a function of many interdependent and interacting factors including soil, water, plant and weather, it is extremely difficult to isolate specifically the effect on crops due to a specific amount of applied irrigation water. However, under severe moisture stress, crop yield and consequently, the irrigation benefits must decrease.

Some researchers have had to make certain suitable assumptions regarding crop response functions. DeLucia (1969) assumed a linear relationship between crop yield and moisture status per crop growth stage. Igwe (1976) used a synthetic crop function. Moore (1961) suggests a purely analytical approach.

The crop response functions to be employed in this model will incorporate personal judgment and some important features of earlier models developed and used by Igwe (1976) and Yaron (1971). The relationship between the expected crop yield, the maximum crop yield and the amount of applied irrigation water can be represented by the by the following equations:

$$Y = \lambda' Y_{max} \tag{6-3}$$

$$\lambda' = f(\lambda) \tag{6-4}$$

$$\lambda = \frac{Q \cdot \eta}{CU \cdot A} \tag{6-5}$$

$$0<\lambda<1 \tag{6-6}$$

$$0<\lambda'<1 \tag{6-7}$$

$$\text{for } \lambda' \geq 1 \text{ and } \lambda \geq 1,\ Y = Y_{max} \tag{6-8}$$

where:

Y = expected crop yield in units per acre dependent upon the water supply regimes.

Y_{max} = maximum crop yield under optimum water supply regimes

λ = crop response coefficient

η = overall irrigation system efficiency expressed as a decimal

CU = seasonal consumptive use in feet for the model crop or combination of crops

A = irrigated area in acres

λ' = crop response function shape factor

Q = seasonal acre-feet irrigation diversions

The figures 7-10, 7-11, and 7-12 show the operating characteristic curves and also specify the boundary conditions established for the various irrigation water supply regimes. The expected crop yield is related to the maximum crop yield by the water supply regime and the shape of the crop response function.

6.4.4.2 CROP PRODUCTION COST FUNCTION

The irrigation crop production cost function is another essential input function into the decision theory optimization model development. With the other cost and crop price components, a terminal monetary payoff matrix is generated for the action-state combinations. Once generated, the payoff matrix is transformed to a utility function incorporating the risk response of the irrigator.

The many cost factors occurring in irrigated agriculture are usually grouped into certain cost headings including the operating cost, the capital cost, the ownership cost, the labor cost, and the water assessment cost.

6.4.4.3 UTILITY FUNCTION

Construction of an irrigator's utility curve involves transformation of the terminal monetary payoff into suitable utility values by using certain transformation techniques. Rudolf (1956) suggests using a convenient convex utility function that can be mathematically expressed thus:

$$Y(r) = 1 - e^{-ar} \qquad (6\text{-}9)$$

where:

Y = utility

r = net revenue in dollars

a = decision maker's aversion to risk factor

A large value for a, implies a more conservative decision maker. Manning and Rosenstock (1968) postulate that the utility of a return increases as its monetary value increases but at a decreasing rate. They represent this concept by the following function:

$$\text{Utility} = K(r)^{0.3} \qquad (6\text{-}10)$$

where:

K is an arbitrary coefficient

The weakness of both postulated functions is the difficulty in arbitrarily choosing suitable values for those factors that would closely describe the irrigator's attitude toward risk.

The technique most frequently prescribed and actually utilized in generating utility functions in decision theory models has been generally attributed to the model first developed by von Neumann and Morgenstern (1944).

This model, generally known as N-M model, is based on a continuity assumption which is stated as follows:

$$(P) \cdot U(X_1) + (1-P) \cdot U(X_3) = U(X_2) \qquad (6\text{-}11)$$

where:

$U(X_1)$ = utility of X_1 outcome

$U(X_2)$ = utility of X_2 outcome

$U(X_3)$ = utility of X_3 outcome

$X_1 < X_2 < X_3$

P, and (1-P) = 'conjugate' probabilities associated with X_1 and X_2 outcomes

To develop a utility cruve, X_1 and X_3 outcomes are arbitrarily assigned known utility values. Once this is done, any intermediate utility for any outcome such as X_2 can be easily established by simple computation using the N-M continuity equation.

The N-M model approach is adopted in this study, in developing a typical irrigator's utility function. Steps used in developing a function are as follows:

Step 1. From the generated terminal monetary payoff series, the upper and lower monetary values are assigned extreme utility values in this manner:

	Monetary Values	Arbitary Assigned Utility Values
Upper Limit	+ $A	A
Lower Limit	- $A	C

These figures already establish two points on the curve of utilities as a function of monetary values.

Step II. A hypothetical decision problem is created that would have two possible alternatives and three possible outcomes. This can be shown diagramatically (Fig. 6-4).

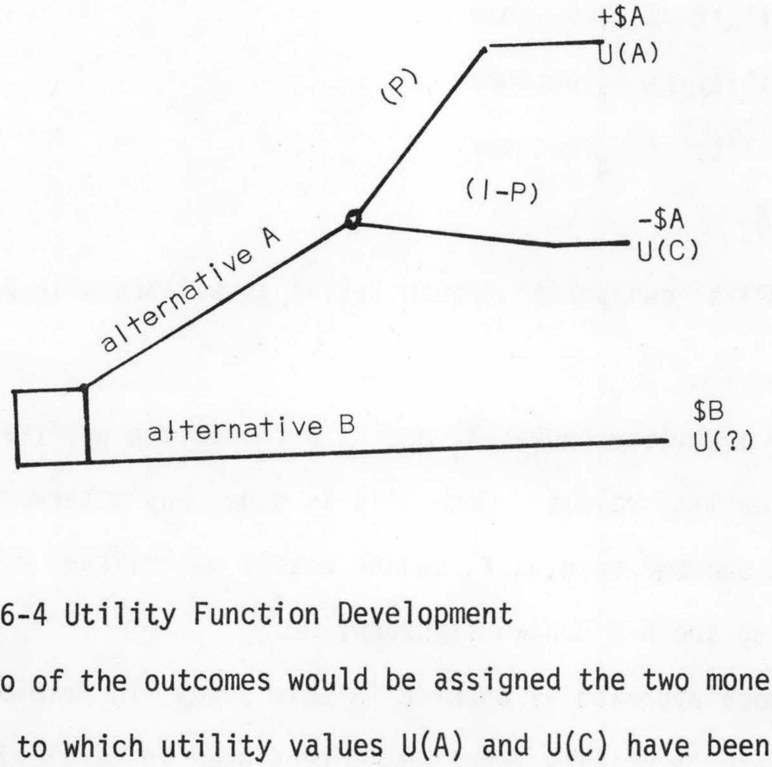


Figure 6-4 Utility Function Development

Two of the outcomes would be assigned the two monetary values $A and -$A to which utility values U(A) and U(C) have been respectively assigned. In alternative A, the probability of gaining $A monetary value that has been transformed to U(A) utilities, is P; while the probability of losing -$A monetary value transformed to U(C) utilities would be (1-P). A question is posed regarding how much the irrigator is willing to pay as insurance for that gain of $A. If the answer is $B monetary value, then the utility of $B is determined using the N-M continuity equation in the manner:

Utility of \$B = P(U(A)) + (1-P) (U(C)) (6-12)

Once the utility of $B is determined, other intermediate utilities are similarly computed until sufficient points are generated to establish a utility function. To be suitable for incorporation into the study model, an equation for that utility as a function of monetary payoff, that is

$U = f(MP)$, must be written

A utility function can possess three general configurations, all of which increase monotonically (Figure 6-5).

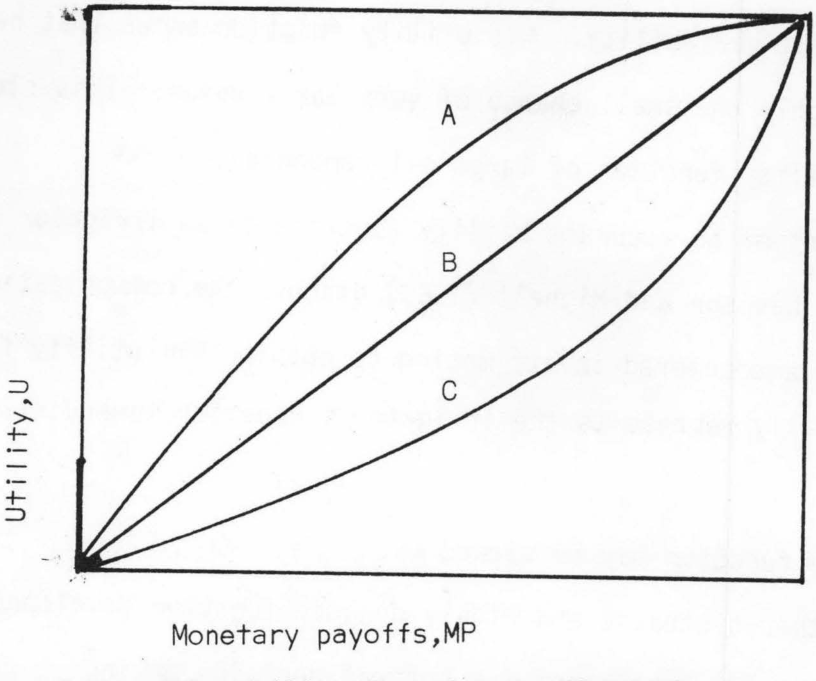


Figure 6-5 Possible Utility Function Configurations

Each utility function represents a particular individual's or group's risk response. Individual A has a diminishing marginal utility of money, that is $^{d^2U}/d^2MP < 0$. This shows that as dollar gains increase, they become subjectively devalued, implying the individual's conservative tendencies. In a risky situation he would prefer the action with lower variability, even though both actions have the same expected monetary value.

Individual B has a constant marginal utility of money, that is, $^{d^2U}/d^2MP = 0$. This implies that he regards an additional dollar income just as highly regardless of whether it is the first dollar or the one millionth.

Individual C subjectively values each dollar gain more highly, that is, $\frac{d^2U}{d^2MP} > 0$. This individual is a risk taker who prefers an action with great variability. His utility function shows that he values very highly the small chance of very large gains. This closely depicts the utility function of large oil companies.

Development of an accurate utility function of an irrigator is not an easy task. Davison and Mighell (1963) discuss the communication problems often encountered in attempting to obtain the utility function that realistically represents the irrigator's behavior toward risk and uncertainty.

A utility function may be viewed as:

1) A rather synthetic and highly dynamic function developed such that it is logically consistent for optimal decision making.

2) Development of a utility function is similar to calibration of a piece of equipment.

3) Due to the degree of subjectiveness or arbitrariness in developing the function; no material significance can be attached to its relative magnitude other than being a decision making tool.

Excellent detailed treatments of utility theory and curve generation can be found in these references by Chernoff and Moses (1959), Fishburn (1967), Schlaifer (1961), and Schlaifer and Raiffa (1960), Officer and Halter (1968), Halter and Dean (1971), and Pratt (1964).

6.5 DECISION STRATEGY DEVELOPMENT

Under hydrologic and irrigation efficiency uncertainty regimes, an irrigator or irrigation district may make the management adjustment of deciding what area of land to commit to irrigation. For such a case, the area, A_j, therefore, becomes an essential decision variable whose optimum value should be obtained. This implies that all other input factors should be expressed as functions of the area, A_j.

Upon the foundation of a simplistic conceptual model, a final working model is typically constructed.

6.5.1 CONCEPTUAL MODEL: DETERMINISTIC APPROACH

When the decision is to irrigate just one acre of land under a single crop, j, the terminal monetary payoff function for this action can be formulated as follows:

$$\pi = P_c Y - P_w q - OP - CP - OW - LA \qquad (6\text{-}13)$$

where:

π = farm income in dollars for that decision to irrigate just one acre under a single crop, j

P_c = unit price in dollars received from harvested crop

Y = expected crop yield in units per acre dependent upon the water supply regimes

P_w = per acre-foot water assessment in dollars

q = applied irrigation water in acre-feet per acre

OP = per acre irrigation crop production operating cost in dollars

CP = per acre irrigation crop production capital cost (interest on capital investment) in dollars

OW = per acre irrigation crop production ownership cost (depreciation, taxes and insurance) in dollars

LA = per acre irrigation crop production labor cost in dollars

However, if the decision is to irrigate, A_j, acres of land under a single crop, j, then the total monetary payoff function becomes:

$$\pi A_j = (\pi + P_w q)A_j - P_w Q \qquad (6\text{-}14)$$

where:

πA_j = the total monetary payoff function for irrigating, A_j, acres under a single crop, j

Thus, πA_j, now becomes the objective function for a deterministic case where the assumption is that the water supply regime is sufficient for optimum crop yields.

The objective function, πA_j, for a less-than-reliable water supply case becomes:

Max: $Z = \pi A_j$,

Subject to the boundary conditions established by the crop response functions in this manner:

1) $\lambda \geq 1$, implies a sufficient irrigation water supply with $Y = Y_{max}$

2) $0 < \lambda < 1$, implies a range of non-optimal water supply with $Y = \lambda' Y_{max}$

3) $\lambda = 0$, an extreme dry condition occurs with $Y = 0$

Optimality is dependent upon the computation of that area, A_j, that maximizes the objective function, πA_j, subject to the specified constraints. This is mathematically expressable as the derivative of the objective function πA_j, with respect to the area, A_j, and equating to result to zero

ie $$\frac{d(\pi A_j)}{d(A_j)} = 0, \qquad (6\text{-}15)$$

and computing that, A_j

Depending on the form and complexity of the response surface generated, obtaining a global optimum may require the application of a search technique.

6.5.2 DECISION THEORY MODEL FORMULATION

The objective function of the decision theory stochastic optimization scheme can be formulated on the basis of the expected monetary value, EMV, criterion or the expected utility, EU, criterion.

6.5.2.1 DECISION THEORY MODEL FORMULATION: EMV CRITERION

By deciding to irrigate, A_j, acres of land under a single specified crop, j, when the probability, $P(\theta_i)$, of the occurrence of the state of nature, θ_i, for streamflow and the probability, $p(\theta_k)$, of the occurrence of the state of nature, θ_k, for irrigation efficiency are considered, the total expected monetary payoff function, EMP, can be expressed as follows:

$$EMP_{ijk} = \sum_{k=1}^{m} \sum_{i=1}^{n} \left[p(\theta_k) \ p(\theta_i) \cdot \pi_{ijk} \right] \qquad (6\text{-}16)$$

where:

π_{ijk} = the terminal monetary payoff function for deciding to irrigate, A_j, acres of land, under a single crop, j, when i and k are the states of nature considered.

$$\pi_{ijk} = (P_c Y_{ik} - OP - CP - OW - LA)\, A_j - P_w Q_{ik} \qquad (6\text{-}17)$$

$p(\theta_k)$ = the probability of the occurrence of the state of nature, θ_k

$p(\theta_i)$ = the probability of the occurrence of the state of nature, θ_i

$$\sum_{i=1}^{n} p(\theta_i) = 1 \qquad (6\text{-}18)$$

$$\sum_{k=1}^{m} p(\theta_k) = 1 \qquad (6\text{-}19)$$

n = number of the considered hydrologic states of nature

m = number of the considered irrigation efficiency states of nature

A_j = area in acres under crop, j

Q_{ik} = seasonal acre-feet irrigation diversion available when i and k are the states of nature considered

Y_{ik} = crop yield in units per acre when i and k are the states of nature considered.

For the EMV criterion, the objective function can be expressed as:

Max: $Z = EMP_{ijk}$

subject to:

$$Y_{ik} = \lambda'_{ijk} Y_{max} \qquad (6\text{-}20)$$

where:

$$\lambda_{ijk} = \frac{Q_{ik} \cdot \eta_{ik}}{CU \cdot A_j}$$

and

$$\lambda'_{ijk} = f(\lambda_{ijk})$$

λ_{ijk} = crop response coefficient in the i and k states of nature

λ_{ijk} = 0 implies an extreme dry condition in the i and k states of nature with $Y_{ik}=0$

$0<\lambda_{ijk}<1$, implies a range of non-optimal water supply regime in the i and k states of nature with $Y_{ik}=\lambda'_{ijk}Y_{max}$.

λ'_{ijk} = crop response function shape factor in the i and k states of nature

η_{ik} = overall irrigation efficiency expressed as a decimal when i and k are the states of nature

The other parameters have been described.

The procedure for obtaining optimality involves deciding that area of land, A_j, that yields the greatest expected monetary payoff, EMP_{ijk}, subject to the imposed constraints.

Figures 6-6 and 6-7 schematically illustrate the decision processes for EMV criterion.

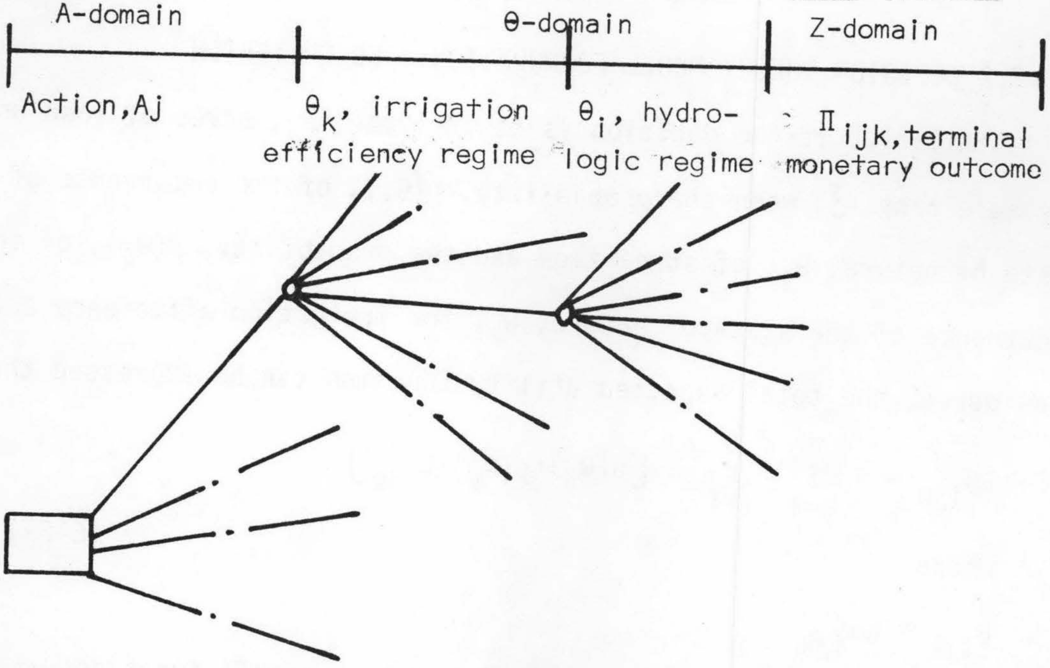


Fig.6-6 Decision Tree for EMV Criterion

Since θ_i, θ_k are stochastically independent, Figure 6-6 can be reduced to Figure 6-7.

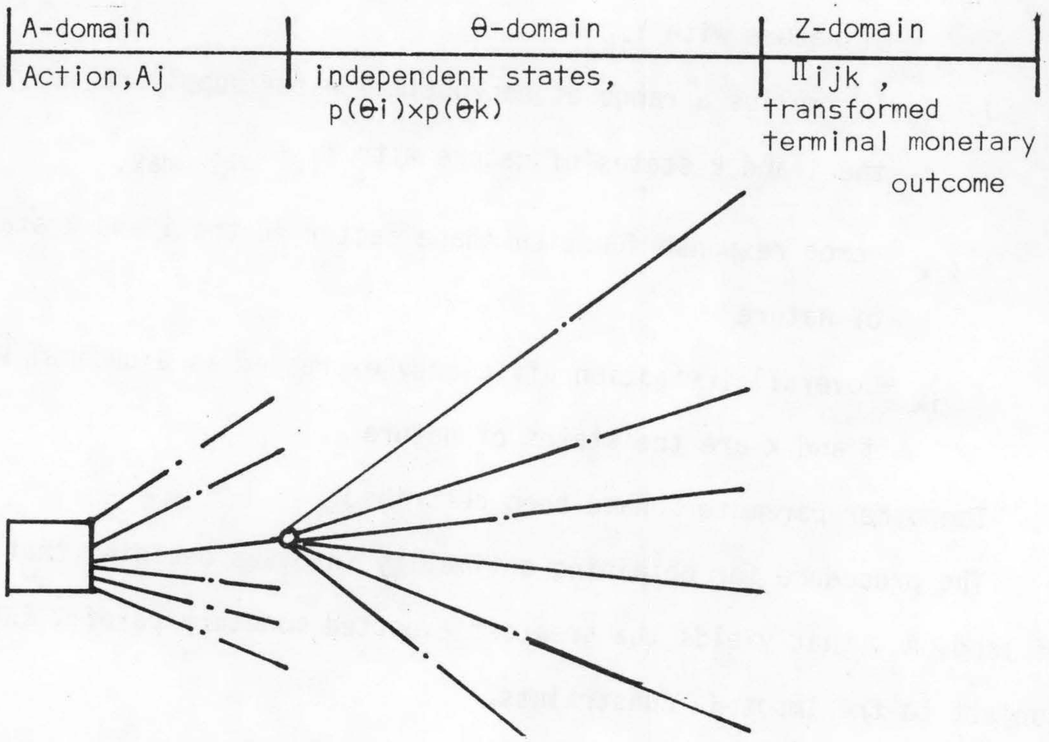


Fig.6-7 Decision Tree for EMV Criterion for Stochastically Independent States,θi,θk

6.5.2.2 DECISION THEORY MODEL FORMULATION: EU CRITERION

Similarly, if the decision is to irrigate, A_j, acres of land under a single crop, j, when the probability, $p(\theta_i)$, of the occurrence of the state of nature, θ_i, of streamflow and the probability, $p(\theta_k)$, of the occurrence of the state of nature, θ_k, for irrigation efficiency are considered, the total expected utility function can be expressed thus:

$$EU_{ijk} = \sum_{k=1}^{m} \sum_{i=1}^{n} \left[p(\theta_i)\cdot p(\theta_k)\cdot U_{ijk}\right]$$

where (6-21)

$U_{ijk} = \alpha\pi_{ijk}$

$\alpha\pi_{ijk}$ implies that the terminal monetary payoff functions, π_{ijk}, must first be transformed to their equivalent utilitiy functions, U_{ijk}.

The other parameters are as earlier described.

For the EU criterion, the objective function can be mathematically expressed as follows:

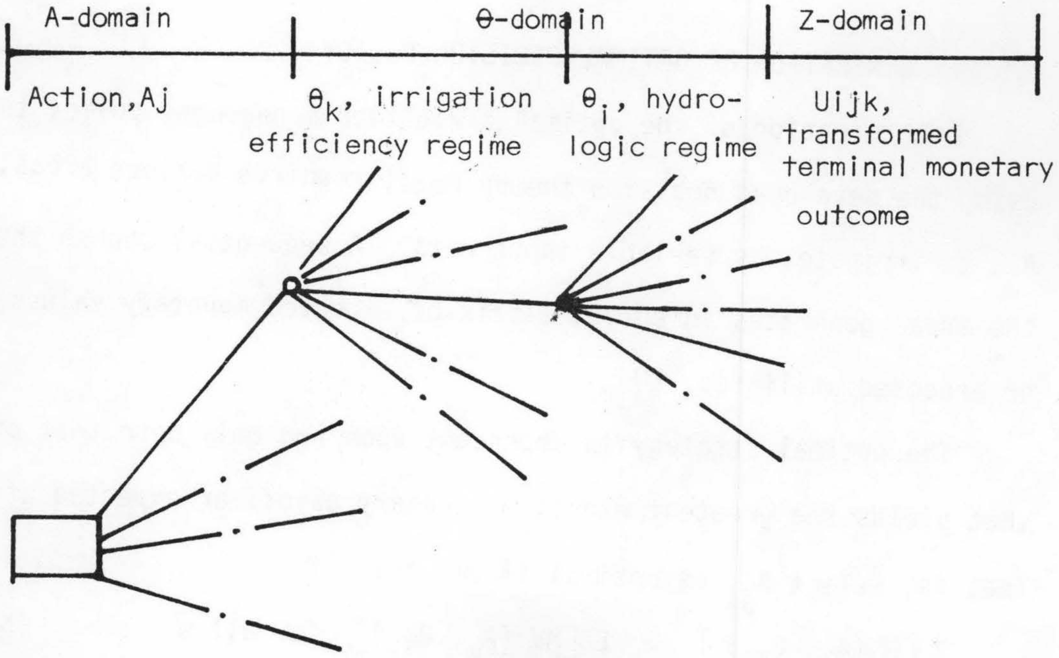
Max: $Z = EU_{ijk}$

similarly subject to the boundary conditions expressed in equation 6-20.

The procedure for optimality determination involves determining that area of land, A_j, that yields the greatest expected utility, EU_{ijk} subject to those specified constraints. This can be mathematically derived by computing the derivative of the objective function, EU_{ijk}, with respect to area, A_j, and equating the result to zero, ie.

$$\frac{d(EU_{ijk})}{d(A_j)} = 0 \quad , \qquad (6\text{-}22)$$

then computing that area, A_j. Figures 6-8 and 6-9 schematically illustrate the decision processes for EU criterion.



Fig, 6-8 Decision Tree for EU Criterion

For stochastically independent θ_i, θ_k, Figure 6-8 can be reduced to Figure 6-9.

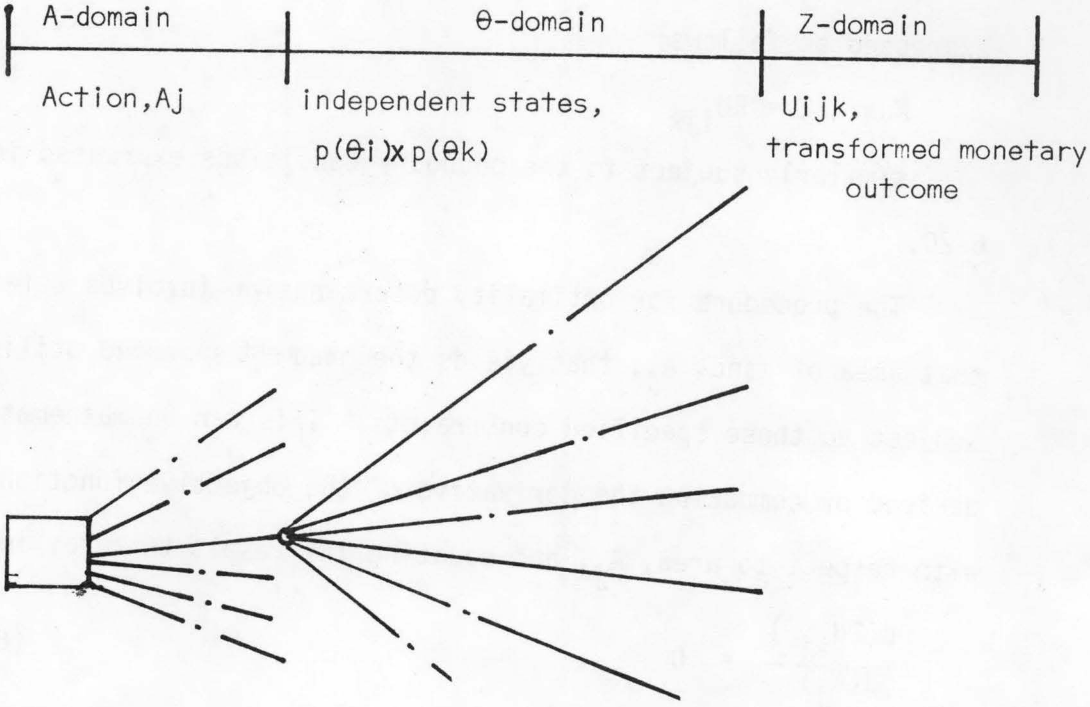


Fig. 6-9 Decision Tree for EU Criterion for Stochastically Independent States,θi,θk

6.5.2.3 GENERATION OF OPTIMAL DECISION POLICY

Determination of the optimal irrigation management policy to adopt using the developed decision theory model requires various areas, A_j, to irrigate, as variable input data. A sequential search through the areas generates an output matrix of expected monetary values, EMV, or expected utilities, EU.

The optimal strategy is dependent upon and only upon that area, A_j, that yields the greatest expected monetary payoff or expected utility. That is, select A_j as optimal if and only if

$$E\left[MV(A_j, \theta_{ik})\right] > E\left[MV(A_w, \theta_{ik})\right] \text{ for all } w \qquad (6\text{-}23)$$

or

$$E\left[U(A_j, \theta_{ik})\right] > E\left[U(A_w, \theta_{ik})\right] \text{ for all } w$$

where

E means expected,

U means utility, and

MV means monetary value

6.6 MODEL ASSUMPTIONS

Certain assumptions were made in the development of the decision theory model. Obtaining an optimal irrigation policy would necessitate complete compliance with the following:

1) Natural stream flow without storage is the main irrigation water supply source.

2) All streamflows entering the irrigation project are entirely dedicated to irrigation purposes and must be paid for. Any unused diverted stream is lost on leaving the project area.

3) The price assessed for water includes all delivery charges up to the rootzone.

4) Consumptive use of water for a single crop or combination of crops is constant season after season.

5) All rainfall events within the active irrigation period are regarded as noneffective and thus do not significantly contribute to the soil moisture status.

6) Irrigable land area is not a limiting production input.

7) Economy of scale is not explicity considered.

8) Irrigation efficiency and streamflow are considered mutually exclusive or probabilistically independent events. Thus, the probability of the joint occurrence of the events is the product of their separate

probabilities of occurrence. This is the multiplication probability rule.

6.7 GENERATING THE POSTERIOR PROBABILITY DENSITY FUNCTION USING BAYESIAN METHODOLOGY

Elsewhere in this study, Bayesian statistical decision strategy as a rather complete tool for decision-making in the face of uncertainty has been treated extensively. In the absence of data or adequate data, subjective prior probability assignments to the states of nature due to streamflow and irrigation efficiency are permitted. However, as information becomes available through experimentation or forecast, those subjective probabilities can then be refined and updated using the Baye's theorem.

Useful information regarding the available quantity of water in a stream for irrigation can be estimated with some fair degree of accuracy by examining catchment snowpack data, reservoir configuration, stream gaging data and other hydrometeological data. Furthermore, measurements of irrigation efficiency can periodically be undertaken once the irrigation system is physically in place.

Information derived from experimental observations and forecasts, can then be combined with the prior subjective probabilities and input into a Bayesian theoretic framework to yield refined and updated posterior or conditional proability density functions, in this manner:

$$P(\theta/Z) = P(\theta)\cdot P(Z/\theta)/P(Z) \qquad (6\text{-}24)$$

in which,

$P(\theta/Z)$ = posterior probability for the occurrence of a particular state of nature, θ, given an experimental result, Z.

$P(\theta)$ = prior probability

$P(Z/\theta)$ = conditional probability

$P(Z)$ = probability from experiment

This Bayes' theorem can be written in a more general form thus:

$$P(\theta_K/Z) = \frac{P(Z/\theta_K)P(\theta_K)}{\sum_{i=1}^{n} P(Z/\theta_i)P(\theta_i)} \tag{6-25}$$

that is:

$$P(\text{state/sample}) = \frac{P(\text{sample/state})\ P(\text{state})}{\sum_{\text{all states}} P(\text{sample/state})\ P(\text{state})} \tag{6-26}$$

in which:

θ_K = unknown states of nature

Z = observed sample

n = all considered states

Once the posterior probability density functions, $P(\theta_K/Z)$, are computed, they are then substituted back in the model in place of the prior probability density functions to determine a new optimal policy, that is, the decision that maximizes expected utility based on the new data.

In most cases, experimentation or forecast activities imply a large investment in time and money that sometimes creates doubts regarding the real value of the decision to acquire more information, whether or not refined probability estimates significantly impact optimal decision, or the extent of the effort that should be expended in obtaining information. Generally, determination of how much the expected utility has increased due to the decision to obtain more information can be a scale for evaluating the utility of experimentation. Therefore, the value of experimentation can be determined by computing the difference in the expected value before and after experimentation. This difference sets the upper limit of the value of information (de Neufville and Stafford, 1971).

CHAPTER VII

APPLICATION OF DEVELOPED MODEL TO THE WOOD RIVER VALLEY IRRIGATION DISTRICT NO. 45

To accomplish the specified study objectives, the following steps must be followed:

1) Select the study area to apply the model.
2) Specify the investigative pattern.
3) Analyze the available data in the following sequence:
    a. Statistically analyze the historic hydrologic events by generating their discrete probability density functions.
    b. Determine the consumptive use, CU, of each irrigated crop.
    c. Derive the discrete probability density function for the specified irrigation efficiency regimes.
    d. Develop the irrigation crop production cost functions.
4) Select suitable crop response functions.
5) Develop the utility function for the selected study area.
6) Develop a computer routine incorporating irrigation diversions and irrigation efficiency probability density functions, utility, crop response and irrigation crop production cost functions and consumptive use.
7) Analyze the results.
8) Conduct post optimal analyses.

7.1 DESCRIPTION OF THE STUDY AREA

The model construction was described in Chapter 6. The main functions the model are designed to perform are contained in the study objectives. The Wood River Valley Irrigation District No. 45 was selected as the study area based on the following criteria:

1) Availability on long-term basis of such relevant data as irrigation diversions, crop consumptive use, and crop distribution.

2) Availability of reports on current economic studies (farm budget analyses) for the area. From the reports, the irrigation crop production cost function can be developed.

3) Due to the extent and character of the cumulative decreed water rights for the district, irrigation water diversions closely reflect the natural stream flow pattern (Figure 7-1).

4) Long-term history of persistent inadequate irrigation water availability during the late cropping season.

5) Though decreed water rights seem to be more than adequate for crop production, the overall canal system configuration, management, maintenance and operations seriously limit the seasonally cropped acreage.

6) An open canal system and irrigation by flooding exist in the District.

7) Willingness of the District personnel in providing relevant information and records.

The Wood River Valley Irrigation District No. 45 lies entirely within the Bellevue Triangle; a mountain valley located in central Blaine county, Idaho. Bellevue itself, situated at about 1500 meters (4921 feet) elevation, is in the north. Foothills flank the east and west sides, and Picabo and Timmerman Hills border the south; thus roughly creating a triangle. The district is approximately 3310 hectares (8177 acres) in land area (Figure 7-2).

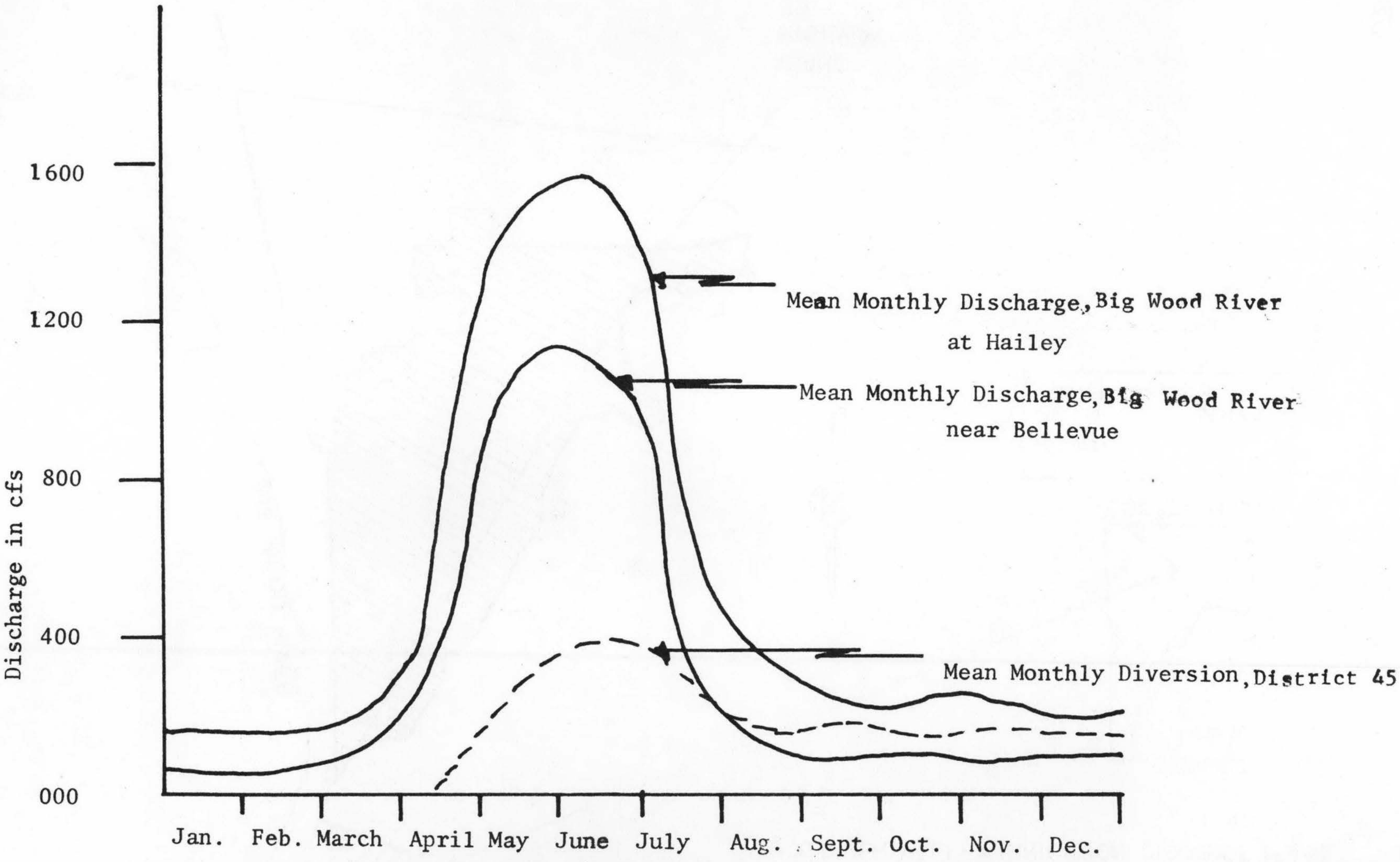


Fig.7-1 The Big Wood River Mean Monthly Discharge and The Irrigation District No.45 Mean Monthly Diversion.

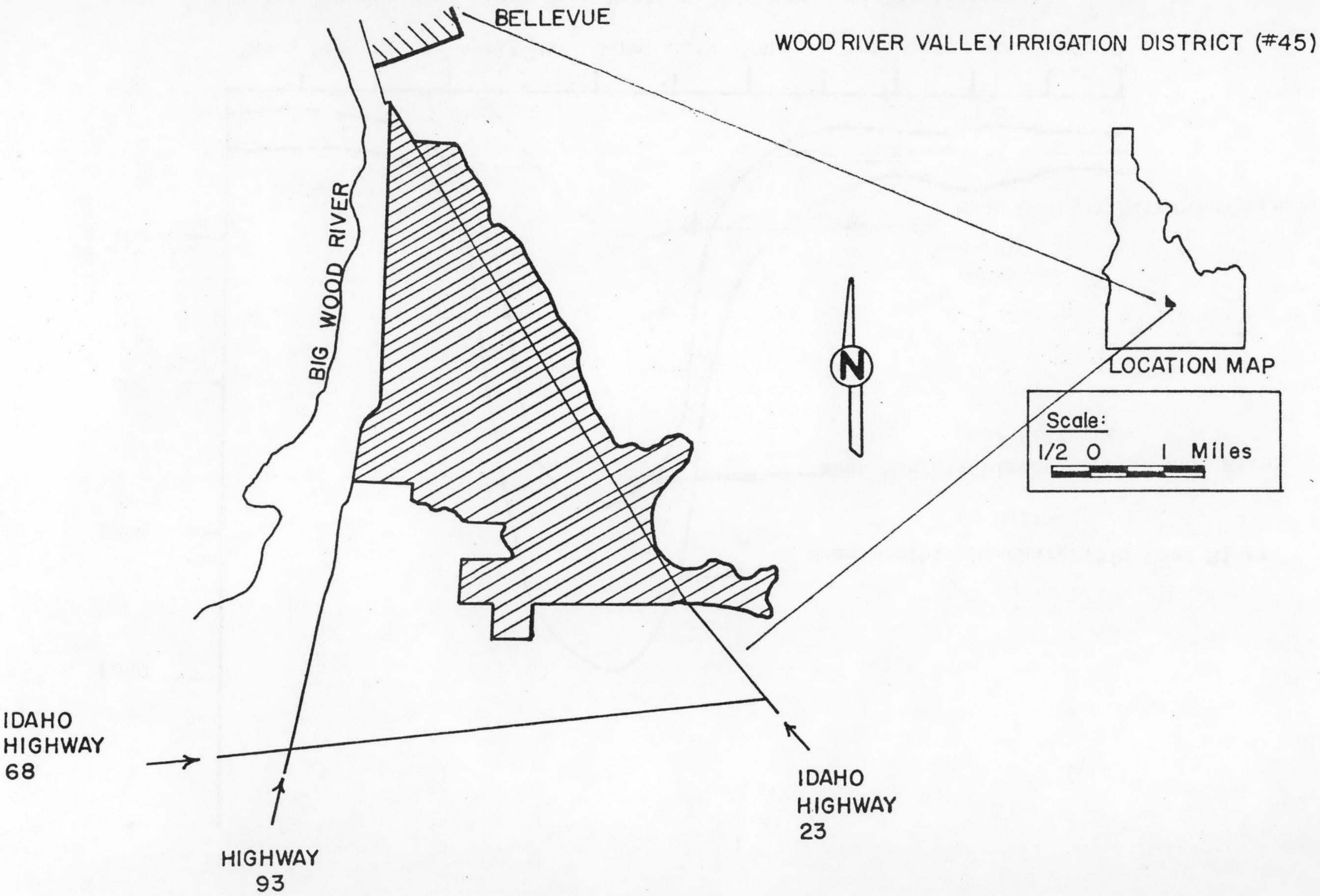


Fig.7-2 The Wood River Valley Irrigation District NO.45 Service Area Map.

The Big Wood River with its source in the rugged mountains of the Sawtooth National Forest, flows south and enters the Bellevue Triangle at Hailey. From Hailey the river continues south and west to the Magic Reservoir, and thence to the Snake River below Hagerman. The drainage area of the river, north of Hailey, is roughly 1658 square kilometers (640 sq. miles).

Three main canal systems totaling approximately 39 kilometers (24 miles) long divert irrigation water from a common point on the Big Wood River. About 2797 hectares (6912 acres) in District No. 45 are presently being irrigated from the canal systems.

High seepage losses, lack of maintenance of the canal access roads, and water control structures, insufficient, inefficient and inappropriate water measuring devices, and inadequate canal system capacity plague the system. These factors contribute to an inadequate water supply reportedly occurring during the last half of the irrigation season.

The entire canal system is constructed on highly permeable Little Wood River gravelly loam soils. Two independent studies conducted by the U.S. Soil Conservation Service and the University of Idaho Water Resources Institute, reported large seepage losses occurring in the canal system (Brockway and Irvin, 1975 and Wood River Valley preliminary report, 1964). Certain proposed alternatives for improving the District water supply include canal lining with bentonite and concrete, canal replacement with pipelines, canal consolidation, well development, pumped storage and improvement in the overall canal operation, maintenance and management.

In 1948 and 1949 canal sections lined with bentonite failed as the bentonite was eroded away within a short time. Replacing the canals with pipelines would eliminate seepage losses. However, the benefits accruing from increased crop production must first be matched with the project costs to determine the most economical action.

Additional water could possibly be provided to the area by constructing storage on the Big Wood River. However, more than 15 wells would be pumped into storage during the winter months for use during the irrigation season. This is possible since an extensive aquifer system underlies the area (Jensen, 1975). Large amounts of irrigation on the very permeable gravelly soils would continue recharging the aquifer system.

The Wood River Valley Irrigation District No. 45 is a legally organized water users association serving 32 stockholders. A three member board of directors is the governing body.

The decreed water rights date between 1881 and 1952. Available records show rights for 1881 to 1902 to be 343.8 cfs. The 1902 and subsequent water rights that are entirely flood rights amount to 100 cfs. The maximum monthly diversion during the recorded period of 1928 to 1973 was 508 cfs. However, diversions have sometimes exceeded this quantity due to irrigators using early season diversions for filling the soil profile and building up the water table.

In the early part of the irrigation season, the irrigation diversions would normally be enough to supply the decreed rights. However, diversions naturally decline dramatically in response to the stream flow regime.

The climate in the area is characterized by moderately cold winters and warm summers. The annual precipitation measured at Hailey averages 386 mm (15.2 inches), 163 mm (6.5 inches) of which occur during the months of December, January and February. Only 42 mm (1.7 inches) occur during July, August and September (Figure 7-3).

The major crops are hay, wheat, barley, oats and pasture. The hay/grain rotation on most operations averages 6 to 8 years of hay followed by 2 years of grain. The average growing season of 90-100 days begins in mid-May and ends in September.

Under adequate water supply regimes, alfalfa could yield an average of 3.5 to 4 tons per acre in 2 cuttings. Grain yields average 45 to 50 bushels per acre. Alfalfa usually receives six irrigations (three per cutting), while grains normally receive four to five irrigations.

As a result of short water supply occurring after July 15, crop yields may decline by 25 percent. Most farmers in the area speculate that late season irrigation accounts for the difference between 30 and 40-50 bushels of grain yield per acre and between 2-1/2 -- 3 tons and 4 tons of alfalfa per acre.

Presently, the area served by the District is experiencing dramatic land use adjustments and agricultural technological transformation. South of the District, individual well development by farmers to supplement late season streamflows has also increased in the last few years.

Currently, about 1/4 of the District is sprinkler irrigated, 1/2 is surface irrigated and the remaining 1/4 is not irrigated. The

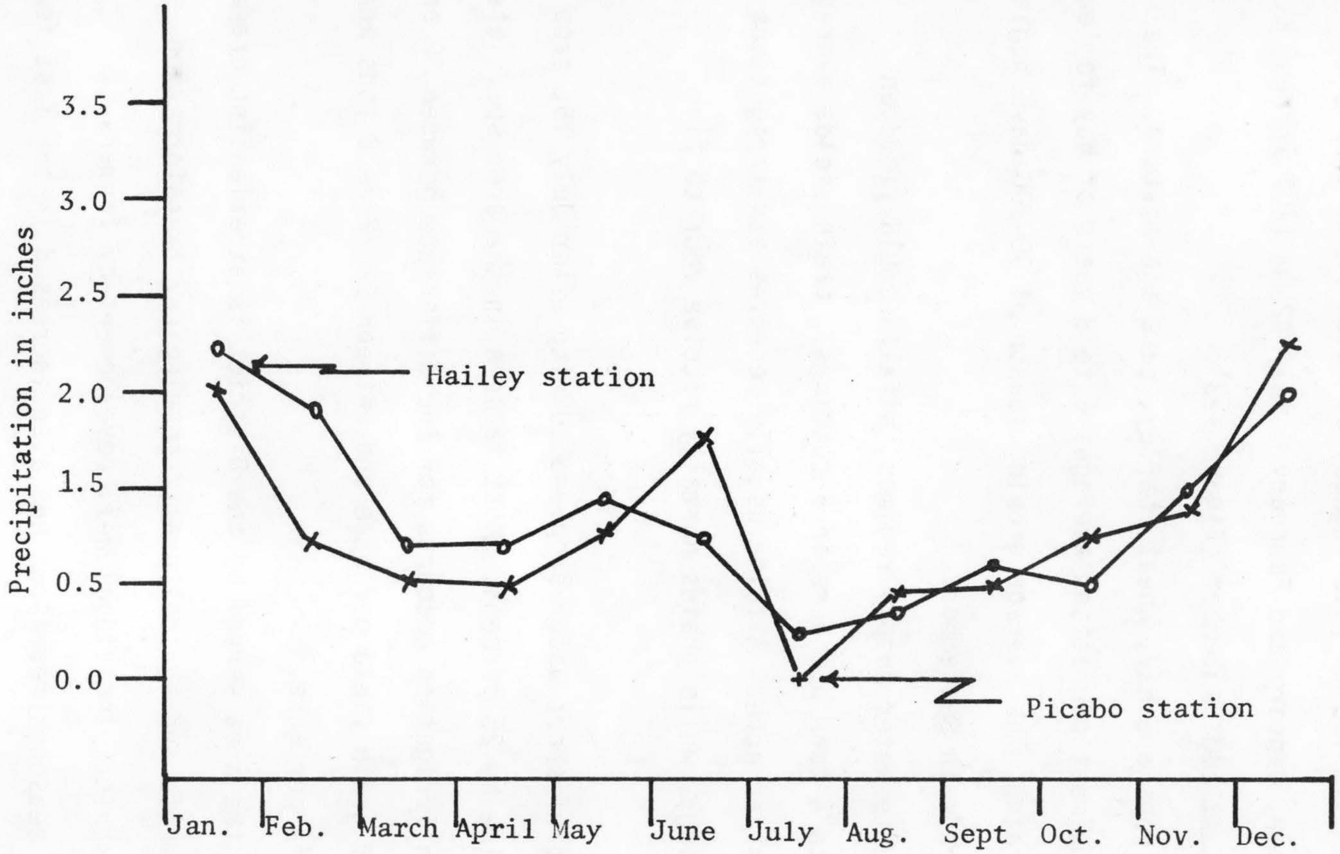


Fig.7-3 The Historic Average Monthly Precipitation for Picabo and Hailey Stations

change to sprinkler systems began in 1972. Such change would obviously greatly reduce applied irrigation water and consequently reduce the aquifer recharge. Subsequently, the Silver Creek flow would decline (Jensen, 1975). The total water supply regime would, however, not materially change. Due to the permeable soil characteristics, any non-consumptively used irrigation water would eventually re-enter the aquifer system or return to the river.

7.2 THE INVESTIGATION PATTERN

Three development investigation phases were created in applying this model to the Wood River Valley Irrigation District No. 45.

In phase I, the following were considered:

1) Probabilistic irrigation diversions.
2) Deterministic irrigation efficiency.
3) Deterministic consumptive use for the specified crop.
4) Single-crop system-alfalfa.
5) Alfalfa irrigation cost function.
6) Exponential type crop response function.

The phase I study pattern was designed to represent a more traditional approach in the irrigation decision-making process.

In phase II, the following were considered:

1) Probabilistic irrigation diversons.
2) Probabilistic irrigation efficiency utilizing a normal distribution postulate.
3) Deterministic consumptive use for the specified crop.
4) Single-crop system-alfalfa.
5) Alfalfa irrigation cost function.

6) Three crop response functions; the linear type, the exponential type, and the polynomial type (power).
7) Probabilistic irrigation efficiency utilizing a log-normal distribution postulate and repeat of steps 1, 3, 4, 5 and 6.

Phase II thus directly incorporated the inherent variabilities in the hydrologic and irrigation efficiency phenomena. It, therefore, clearly represented a refinement of the traditional approach in phase I. However, a single crop system was the obvious limitation of the modeled system.

Phase III was similar to phase II except that it incorporated instead, a multi-crop system; wheat and alfalfa. A weighted consumptive use and a multi-crop irrigation cost function were, therefore, generated.

7.3 DATA ANALYSES

The main objective of this study is to develop a probabilistic model for irrigation decision-making that incorporates the randomness and uncertainties inherently associated with the hydrologic and irrigation efficiency events. A relative frequency approach, when applicable, may be used in the probability density function generation because it facilitates data organization and can also provide meaningful and more useful information concerning the likelihood of occurrence of the random phenomenon of interest.

A large volume of long-term observed data of the hydrologic and irrigation efficiency random events is available or can be derived for the study area. Statistical analyses were, therefore, conducted to determine the required probability density functions for the unknown states of nature.

7.3.1 STATISTICAL ANALYSIS OF IRRIGATION DIVERSION EVENTS

In the Wood River Valley Irrigation District No. 45, the total seasonal irrigation diversions frequently exceed crop water requirements. However, the irrigation water supply is frequently inadequate during the late portion of the irrigation season. Therefore, it was considered logical and meaningful to break up the irrigation diversion data into two distinct periods, P1 and P2. The period, P1, covers diversions between May and mid-July, while the period, P2, is between mid-July and September. These periods conform with the two alfalfa cutting periods in the district. With the creation of these periods, the impact on the decision process of the inadequate late season water supply could be adequately investigated that otherwise would be hidden using total irrigation diversions.

Separate frequency analyses were conducted for each period by establishing seven class intervals representing seven hydrologic regimes. Each class interval specifies a range of irrigation diversions for that hydrologic regime and additionally describes the unknown state of nature that can occur. Using the frequency of occurrence of observed data within specific regimes, the probability density functions were derived for each period (Tables 7-2 and 7-3). A similar frequency analysis was conducted using the total seasonal irrigation diversions. That is one period, PT, was considered for the entire irrigation season (Table 7-4).

Irrigation diversion records for the study area have been kept at the Water-Master's Office, Shoshone, since 1922. Thus, 56 years of daily data were available (Table 7-1).

The discrete irrigation diversions and the associated probability density functions generated were input into the investigation model phases I, II, and III described in Section 7-2.

Table 7-1. Historic Irrigation Diversions for the Wood River Valley Irrigation District No. 45

Water Year	Diversion for Period, P1 1/ ($\text{ac-ft}\times10^{-3}$)	Diversion for Period, P2 2/ ($\text{ac-ft}\times10^{-3}$)	Total Diversion 3/ ($\text{ac-ft}\times10^{-3}$)	Diversion for Period, P1 4/ (ac-ft/ac)	Diversion for Period, P2 5/ (ac-ft/ac)	Diversion for Period, PT 6/ (ac-ft/ac)
1922	31.70	21.20	52.90	4.53	3.03	7.55
1923	28.00	21.40	49.50	4.00	3.06	7.06
1924	17.50	2.40	19.90	2.50	0.34	2.85
1925	33.80	17.80	51.60	4.83	2.54	7.38
1926	21.00	4.40	25.40	3.00	0.63	3.64
1927	29.20	18.60	47.80	4.17	2.66	6.84
1928	36.00	10.90	46.90	5.14	1.56	6.71
1929	26.30	3.50	29.80	3.76	0.50	4.26
1930	34.80	11.00	45.80	4.97	1.57	6.54
1931	16.40	2.20	18.60	2.34	0.31	2.66
1932	34.10	15.40	49.50	4.87	2.20	7.07
1933	24.70	8.70	33.40	3.53	1.24	4.77
1934	13.70	3.20	16.90	1.96	0.46	2.40
1935	33.90	9.60	43.50	4.84	1.37	6.22
1936	29.30	9.80	39.10	4.19	1.40	5.59
1937	27.20	6.30	33.50	3.89	0.90	4.79
1938	41.40	30.60	72.00	5.91	4.37	10.28
1939	28.10	7.60	35.70	4.01	1.09	5.11
1940	28.40	13.20	41.60	4.06	1.89	5.95
1941	44.60	23.00	67.60	6.37	3.29	9.66
1942	32.40	24.50	56.90	4.63	3.50	8.13
1943	43.40	32.70	76.10	6.20	4.67	10.87
1944	40.70	22.40	63.10	5.81	3.20	9.01
1945	40.50	20.50	61.00	5.79	2.93	8.71
1946	47.70	21.80	69.50	6.81	3.11	9.93
1947	49.30	17.20	66.50	7.04	2.46	9.49
1948	47.00	15.70	62.70	6.71	2.24	8.95
1949	44.40	11.00	55.40	6.34	1.57	7.92
1950	49.80	24.30	74.10	7.11	3.47	10.58
1951	51.30	32.50	83.80	7.33	4.64	11.96
1952	48.10	31.80	79.90	6.87	4.54	11.41
1953	50.40	29.20	79.60	7.20	4.17	11.37
1954	50.40	18.30	68.70	7.20	2.61	9.82
1955	39.30	15.10	54.40	5.61	2.16	7.78
1956	46.80	29.90	76.70	6.69	4.27	10.95
1957	37.70	22.40	60.10	5.39	3.20	8.58
1958	48.60	29.50	78.10	6.94	4.21	11.17
1959	39.30	11.90	51.20	5.61	1.70	7.32
1960	33.40	9.40	42.80	4.77	1.34	6.22
1961	29.00	7.50	36.50	4.14	1.07	5.20
1962	45.10	22.40	67.50	6.44	3.20	9.65
1963	45.00	25.20	70.20	6.43	3.60	10.03
1964	40.90	25.00	65.90	5.84	3.57	9.41
1965	46.50	35.70	82.20	6.64	5.10	11.74
1966	39.30	8.80	48.10	5.61	1.26	6.87
1967	48.40	34.80	83.20	6.91	4.97	11.90
1968	41.20	20.60	61.80	5.89	2.94	8.83
1969	50.90	28.70	79.60	7.27	4.10	11.37
1970	49.40	26.50	75.90	7.06	3.79	10.85
1971	45.90	35.20	81.10	6.56	5.03	11.59
1972	54.70	28.80	83.50	7.81	4.11	11.93
1973	42.40	13.60	56.00	6.06	1.94	7.99
1974	52.10	29.00	81.10	7.44	4.14	11.58
1975	45.40	34.30	79.80	6.49	4.90	11.40
1976	42.30	30.40	72.70	6.04	4.34	10.38
1977	18.80	6.20	25.00	2.69	0.89	3.56

1/ Column 2: Period, P1, (May to mid-July) diversions (ac-ft)
2/ Column 3: Period, P2, (mid-July to September) diversions (ac-ft)
3/ Column 4: Period, PT, (May to September) diversions (ac-ft)
4/ Column 5: Period, P1, (May to mid-July) diversions (ac-ft/ac)
5/ Column 6: Period, P2, (mid-July to September) diversions (ac-ft/ac)
6/ Column 7: Period, PT, (May-September) diversions (ac-ft/ac)

Table 7-2. Frequency Distribution of Irrigation Diversions for the Wood River Valley Irrigation District No. 45, for P1 Period (May to mid-July)

Flow Intervals (ac-ft)	Hydrologic Regime	Hydrologic State of Nature, θ_i	Frequency: No. of years observed N_i	Relative Frequency $\frac{N_i}{\Sigma N_i} = P\theta_i$	Commulative Relative Frequency
5000- 9500	Very poor	θ_1	0	0.0	0.0
9500-19500	Poor	θ_2	4	0.07	0.07
19500-29500	Inadequate	θ_3	10	0.18	0.25
29500-39500	Marginal	θ_4	12	0.21	0.46
39500-49500	Fairly Adequate	θ_5	23	0.41	0.87
49500-59500	Adequate	θ_6	7	0.13	1.00
59500-69500	Excellent	θ_7	0	0.0	1.00
			$\Sigma N_i=56$	$\Sigma\theta_i=1.00$	

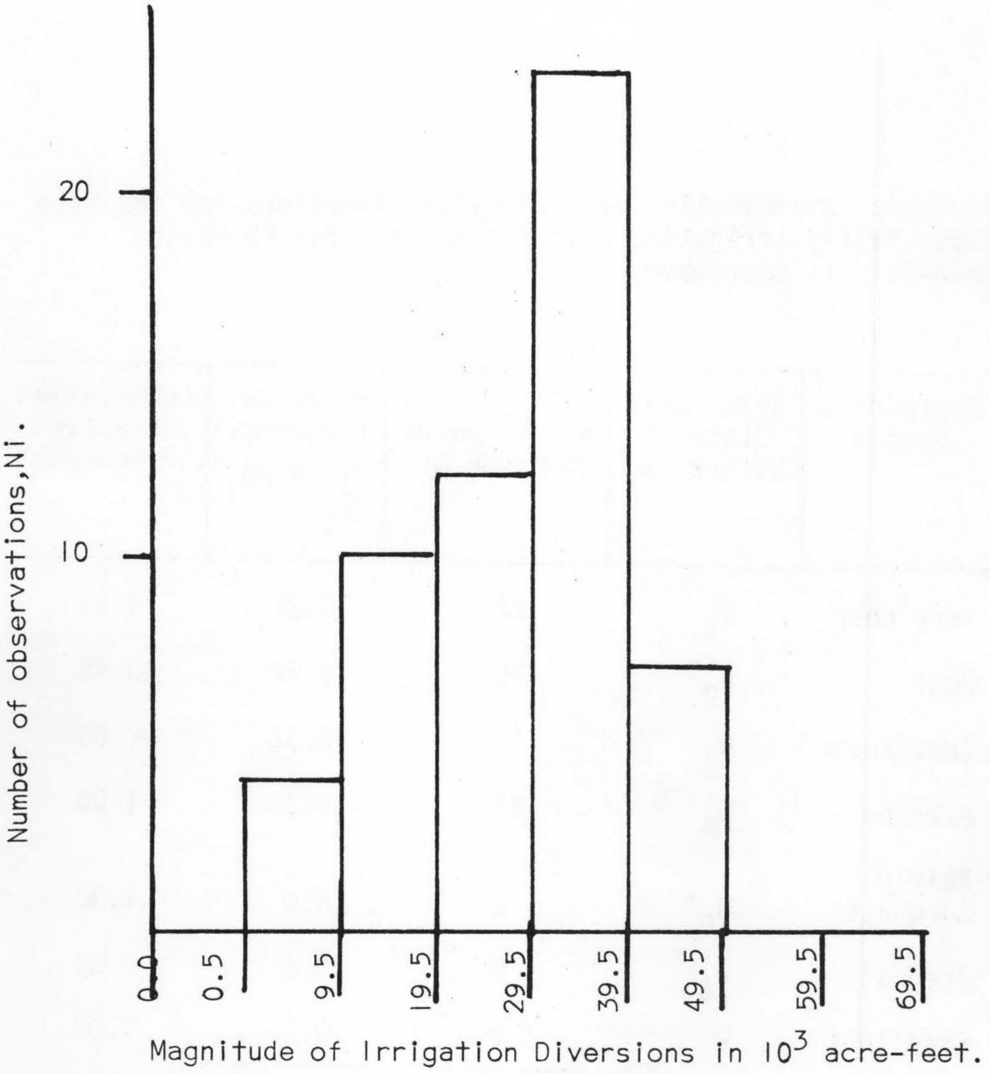


Fig.7-5 Frequency Histogram of Irrigation Diversions for the Wood River Valley Irrigation District No.45,for Period PI(May-Mid-July)

Table 7-3. Frequency Distribution of Irrigation Diversions for the Wood River Valley Irrigation District No. 45, for P2 Period (mid-July to September)

Flow Intervals (ac-ft)	Hydrologic Regime	Hydrologic State of Nature, θ_i	No. of years observed N_i	Relative Frequency $\frac{N_i}{\Sigma N_i} = P\theta_i$	Commulative Relative Frequency
5000- 9500	Very poor	θ_1	12	0.21	0.21
9500-19500	Poor	θ_2	15	0.27	0.48
19500-29500	Inadequate	θ_3	18	0.32	0.80
29500-39500	Marginal	θ_4	11	0.20	1.00
39500-49500	Fairly Adequate	θ_5	0	0.0	1.00
49500-59500	Adequate	θ_6	0	0.0	1.00
59500-69500	Excellent	θ_7	0	0.0	1.00
			$\Sigma N_i=56$	$\Sigma\theta_i=1.0$	

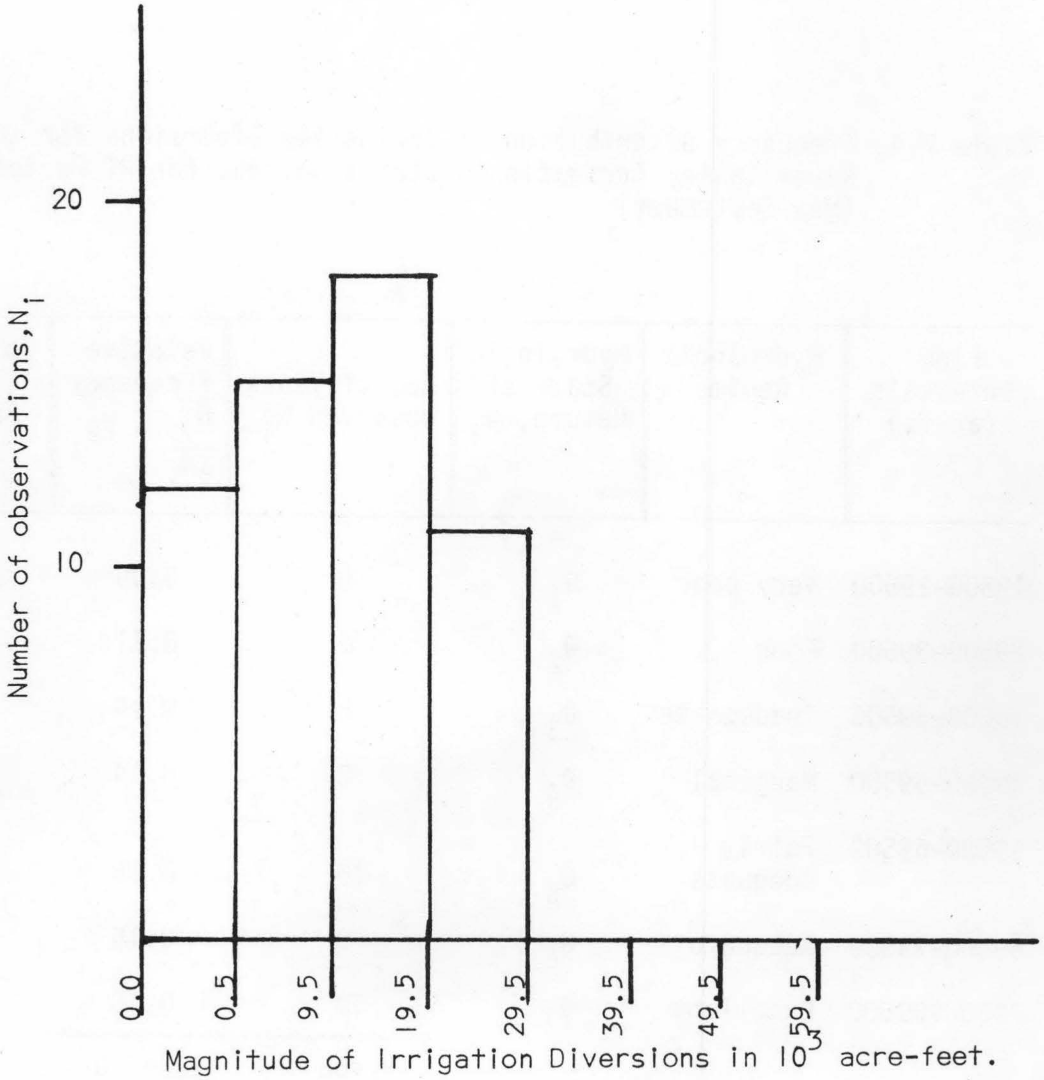


Fig. 7-6 Frequency Histogram of Irrigation Diversions for the Wood River Valley Irrigation District No.45, for Period P2(Mid-July-September)

Table 7-4. Frequency Distribution of Irrigation Diversions for the Wood River Valley Irrigation District No. 45, for PT Period (May-September)

Flow Intervals (ac-ft)	Hydrologic Regime	Hydrologic State of Nature, θ_i	No. of years observed N_i	Relative Frequency $\frac{N_i}{\Sigma N_i} = P\theta_i$	Commulative Relative Frequency
19500-29500	Very poor	θ_1	5	0.09	0.09
29500-39500	Poor	θ_2	6	0.11	0.20
39500-49500	Inadequate	θ_3	8	0.14	0.34
49500-59500	Marginal	θ_4	8	0.14	0.48
59500-69500	Fairly Adequate	θ_5	10	0.18	0.66
69500-79500	Adequate	θ_6	9	0.16	0.82
79500-89500	Excellent	θ_7	10	0.18	1.0
			$\Sigma N_i = 56$	$\Sigma\theta_i = 1.0$	

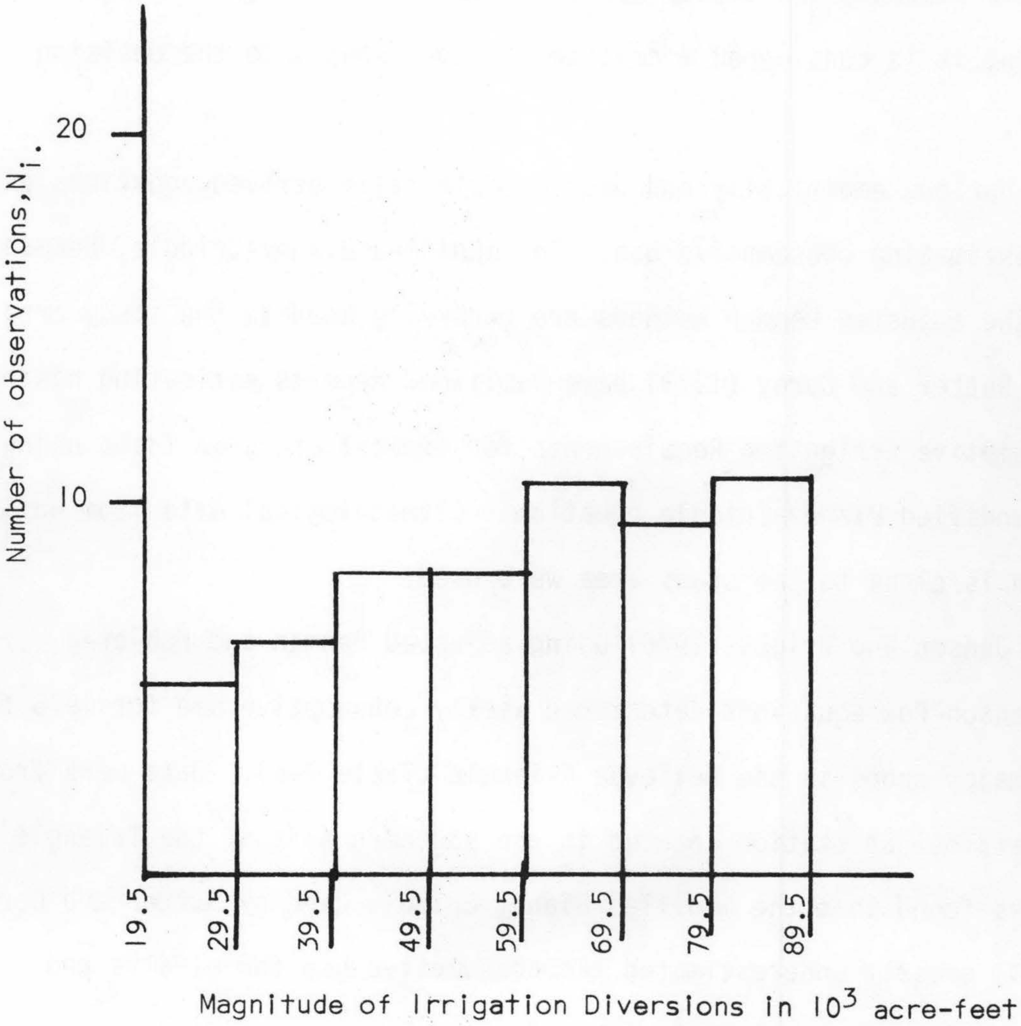


Fig.7-7 Frequency Histogram of Irrigation Diversions for the Wood River Valley Irrigation District No.45, for Period P·T(May-September)

7.3.2 DETERMINATION OF THE CONSUMPTIVE USE OF THE IRRIGATED CROPS

Consumptive use is defined as the sum of that amount of water transpired by plants during the growth process and that amount evaporated from the soil and vegetation in the domain occupied by the growing plants. As this parameter partially specifies the total irrigation water utilization, it is considered a critical factor input into the decision model.

Various empirically and psuedo-empirically derived equations exist for estimating consumptive use. The modified Blaney-Criddle, Penman and the adjusted Penman methods are generally used in the study area.

Sutter and Corey (1970) have published reports estimating historic Consumptive Irrigation Requirements for typical crops in Idaho using the modified Blaney-Criddle equation. Climatological data from Hailey which is close to the study area were used.

Jensen and Wright (1975) using adjusted Penman and Kohler-Nordenson-Fox equations determined weekly consumptive use for 1975 for the major crops in the Bellevue Triangle (Table 7-5). Data were from a climatological station located in the southern part of the Triangle. It was found that the modified Blaney-Criddle used by Sutter and Corey (1970) grossly underestimated the consumptive use for alfalfa and pasture as shown by data in Table 7-7.

Daily consumptive use data for 1976 crops for the study area were generated using the Penman equation. Wind run, relative humidity, and solar radiation data were obtained from the Kimberly Research Station. The Kimberly solar radiation data were adjusted upward to reflect the solar conditions in Bellevue, and the minimum and maximum temperature

Table 7-5 Estimated Daily Evapotranspiration E_{tp} and ET for Specified Crops for the Bellevue Trangle, Idaho[1]

Beginning Day	Potential Evapotranspiration E_{tp} (mm)	Evapotranspiration ET (mm)		
		Alfalfa	Small Grain	Irrigated Pasture
4/12/75	9.2	7.8	7.8	7.8
4/19/75	11.7	9.8	9.8	9.8
4/26/75	18.6	9.3	9.3	9.3
5/03/75	19.5	15.6	15.6	15.6
5/10/75	42.2	19.4	10.1	25.3
5/17/75	36.2	22.8	22.8	22.8
5/24/75	42.2	33.3	10.1	31.6
5/31/75	49.5	46.0	10.9	37.1
6/07/75	50.2	50.2	20.1	37.6
6/14/75	41.6	41.6	27.8	31.2
6/21/75	36.0	36.0	32.1	27.0
6/28/75	47.6	47.6	47.6	35.7
7/05/75	47.4	33.6	49.3	35.5
7/12/75	43.7	21.8	45.4	32.8
7/19/75	46.4	32.9	47.3	34.8
7/26/75	38.9	35.8	37.3	29.1
8/02/75	46.6	46.6	38.2	35.0
8/09/75	41.6	41.6	27.8	31.2
8/16/75	31.1	31.1	15.5	23.3
8/23/75	35.6	35.6	10.0	26.7
8/30/75	33.9	33.9	6.8	25.4
9/06/75	34.1	22.5	6.8	25.6
9/13/75	31.4	17.6	6.3	23.6
9/20/75	28.4	23.0	6.3	21.3
9/27/75	25.9	24.6	6.0	19.4
10/04/75	21.0	20.0	8.4	15.8

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[1] Source is Jensen and Wright (1975) using adjusted Penman equation.

Table 7-6 Estimated Daily Evapotranspiration E_{tp} and ET for Specified Crops for the Bellevue Triangle, Idaho

Date	Potential Evapotranspiration E_{tp} (mm)	Evapotranspiration ET (mm)		
		Alfalfa	Small Grain	Irrigated Pasture
5/17/76	52.13	32.84	32.84	32.84
5/24/76	54.79	43.27	13.15	41.10
5/13/76	52.21	48.62	11.49	39.16
6/07/76	43.92	43.92	17.57	32.95
6/14/76	47.71	47.71	31.98	35.78
6/21/76	59.75	59.75	53.17	44.82
6/28/76	61.60	61.60	61.60	46.20
7/05/76	55.50	39.43	57.72	41.63
7/12/76	48.34	24.22	50.29	36.26
7/19/76	51.48	36.54	53.55	38.63
7/26/76	46.29	42.58	44.45	34.74
8/02/76	39.72	39.72	32.57	29.79
8/09/76	36.07	36.07	24.17	27.06
8/16/76	28.47	28.47	14.25	21.35
8/23/76	40.50	40.50	11.34	30.38
8/30/76	45.74	45.74	9.14	34.30
9/06/76	38.90	25.68	7.78	26.18
9/13/76	20.43	11.43	4.08	15.33
9/20/76	24.56	19.88	5.53	18.42

Table 7-7 Comparison of Monthly ET (mm) Estimates for 1975 Crops for the Bellevue Triangle, Idaho[2/]

		Monthly ET (mm)							
	Crop	April	May	June	July	Aug.	Sept.	Oct.	Total
ARS, Kimberly	Alfalfa	34	101	186	152	172	104	52	715
Sutter & Corey		--	36	120	173	143	46	19	555
ARS, Kimberly	Small Grains	34	59	97	201	101	28	38	486
Sutter & Corey		--	44	118	194	66	1	--	423
ARS, Kimberly	Irrigated Pasture	34	106	142	149	129	99	45	625
Sutter & Corey		10	52	103	148	112	35	7	450

[2/] Source is Jensen and Wright (1975).

data for Hailey were used without adjustment. Using requisite crop coefficients and historic crop distribution data (Table 7-8), total weekly consumptive use was computed for the 1975 and 1976 irrigation seasons for the district. Seasonally cropped area was assumed to be 7000 acres.

As with the irrigation diversion data, the crop consumptive use data for alfalfa only were broken up into two periods, P1 and P2, to conform with the two existing distinct water supply conditions described earlier.

In 1975, the cumulative consumptive use for the period, P1, was 336 mm (1.20 feet). It was 354 mm (1.16 feet) during the second period, P2. The total season consumptive use was therefore 719 mm (2.36 feet). In 1976, the cumulative consumptive use for the period, P1, was 445 mm (1.46 feet), and remained the same as 1975 for the period, P2. The total seasonal consumptive use became 799 mm (2.62 feet).

Historic consumptive use developed by Sutter and Corey (1970) was 335 mm (1.10 feet) for P1 and 354 mm (1.16 feet) for P2. The total season use became 689 mm (2.23 feet).

In this model, the consumptive use parameter was assumed fixed and determinate. The values actually used in the investigation phases I and II where a single crop system of alfalfa was considered were 445 mm (1.46 feet) for the period, P1, and 354 mm (1.16 feet) for the period, P2.

The consumptive use for a multi-crop system was the weighted average for the specified crops. Data of the consumptive use for alfalfa and wheat for 1975 and 1976 are given in Table 7-9. The crop distribution

Table 7-8 Crop Distribution Pattern for the Wood River Valley Irrigation District No. 45[1/]

Crop	Wheat	Barley	Oats	Alfalfa	Irrigated Pasture
Percentage Distribution	6	17	2	58	17

1/ Personal communication with Charles Brockway.

Table 7-9 Monthly Consumptive Use for Alfalfa and Wheat for 1975 and 1976 for the Wood River Valley Irrigation District No. 45

	Alfalfa Consumptive Use (mm)		Wheat Consumptive Use (mm)	
Month	1975	1976	1975	1976
May	141.00	135.16	73.50	88.50
June	185.00	222.72	127.60	141.68
July, 1-15	59.90	87.55	118.30	114.69
Total	385.99	445.43	319.40	344.87
July, 15-30	67.30	83.59	97.10	111.64
August	180.80	161.30	62.10	89.25
September	97.70	107.30	29.60	28.07
Total	345.80	352.19	188.80	228.96

was assumed to be 60 percent alfalfa and 40 percent wheat. The 1976 consumptive use data were used since they were higher than those for 1975. The weighted consumptive use for period P1 was 396 mm (1.30 feet) and for period P2 was 305 mm (1.00 feet). The total season consumptive use for the period, PT, was 701 mm (2.30 feet) for the multi-crop system.

7.3.3 DERIVATION OF THE DISCRETE PROBABILITY DENSITY FUNCTION FOR IRRIGATION EFFICIENCY

As the uncertainty and randomness inherently associated with the irrigation efficiency parameter form the main problem of this study, the discrete probability density function of the occurrence of the various states of nature of this phenomenon must be derived. To assist in this derivation, an assumption must be made concerning the most likely probability function for the variates.

Many probability distribution functions including the binomial, poisson, pearson, normal, lognormal and others, are described in statistics texts (Snedecor and Cockran, 1967, and Benjamin and Cornell, 1970). However, selection and use of any of them largely depends on judgement and subsequent verification using available data. The theoretical interpretation and the mechanics of the physical system must closely match the characteristics of any selected distribution function.

For this study, an assumption was made that the irrigation efficiency random variable is normally distributed. The reasons for this assumption are:

1) Confronted with an irrigation system, a population of experienced irrigation systems design engineers would characteristically assign values to irrigation efficiency parameters ranging from low to high values. The value that would be assigned most often would, however, be concentrated within the mid irrigation efficiency range. The number of assignments for other irrigation efficiency values would typically decrease or "thin down" on both sides of the mid range. Under these postulated conditions, a roughly bell-shaped distribution is envisaged, that is, a normal distribution.

2) A frequency analysis of the irrigation efficiency data computed for the district's irrigation system closely resembles a normal distribution (Figure 7-8). Tests of skewness and kurtosis on the computed efficiencies indicate that this is a good approximation.

3) Benjamin and Cornell (1970) and Snedecor and Cockran (1967) listed certain general conditions based on the central limit theorem, that are desirable for justifying a normal distribution postulate. Irrigation efficiency is a function of many factors including soil, crop, water cost, labor cost, management and others. Under a normal distribution postulate, these factors jointly and additively affect the parameter. If on the contrary, the joint action of these causitive factors is multiplicative, then a log normal transformation of the efficiency variates should be considered. However, as the random variables operating in many natural systems usually arise from a number of additive factors, a normal distribution postulate is generally a good approximation (Huntsberger and Billingsley, 1973).

4) Many engineers have frequently assumed normal distribution even where the specified conditions justifying the assumption were not met because a normal distribution function is analytically tractable and familiar to many researchers.

5) Under certain conditions, some other common distribution functions including gamma, binormal and poisson, usually approximate to a normal distribution.

Obtaining the discrete probability density function for irrigation efficiency employing the normal distribution assumption would be dependent upon generating the population mean, μ, and the population standard deviation, σ, for the random variable. Once determined, the

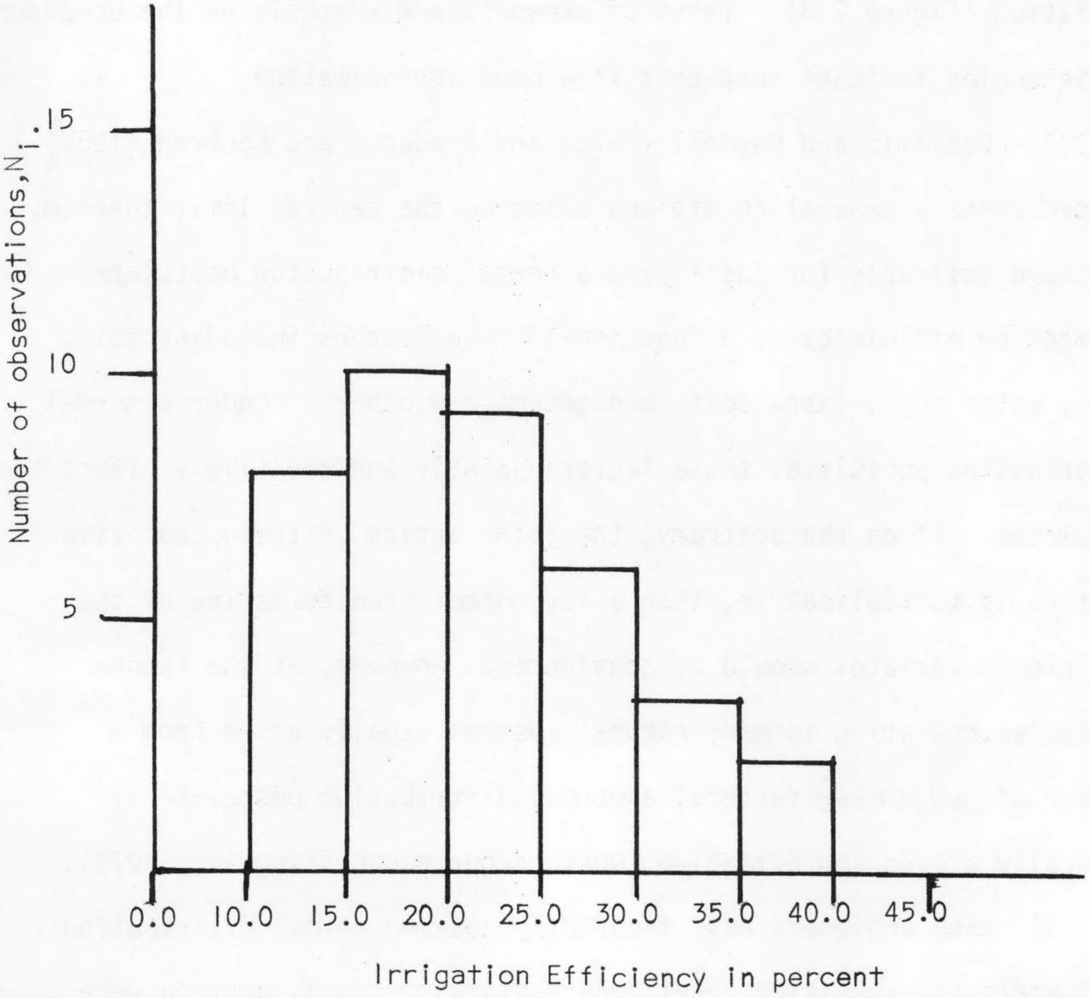

Fig. 7-8 Frequency Histogram of Irrigation Efficiencies for the Wood River Valley Irrigation District No.45

probabilities for the specified state of nature, $\rho\theta\kappa$, can be evaluated using the Z-transformation or the normal distribution equation which is of the form:

$$Z = \frac{1}{\sigma\sqrt{2\pi}} e^{-1/2\ (\chi-\mu)^2/\sigma^2} \qquad (7\text{-}1)$$

using the parameters μ and σ previously described.

Irrigation efficiency was previously defined as that portion of irrigation diversion consumptively used by crops. Irrigation efficiencies were computed for 1975 and 1976 irrigation seasons (Tables 7-10, 7-11). The 1977 efficiencies were not determined because that irrigation water year was considered abnormal. Irrigation diversions declined dramatically. Consequently, it was presumed that irrigation efficiencies would abnormally be high. Worstell (1978) disproved this stating that irrigation efficiencies for 1977 did not materially change. Irrigators adjusted to the situation by reducing the irrigated acreage.

From the results, the population mean, μ, and the population standard deviation, σ, for irrigation efficiency, were evaluated to be 0.21 and 0.068, respectively. A mean, μ, of 0.20 and standard deviation, σ, of 0.07 were used in the modeling process.

Eight discrete states of nature for irrigation efficiency were specified, and their discrete probability density functions, $P\theta_k$, are given in Table 7-12. The irrigation efficiency intervals selected are shown in Figure 7-9.

The investigation Phases II and III which considered probabilistic functions for irrigation efficiency utilized the regimes indicated in Table 7-12.

Table 7-10 Weekly Irrigation Efficiencies for 1975 for the Wood River Valley Irrigation District No. 45

Beginning Date	Irrigation Diversions (ac-ft)	ET (ac-ft)	Irrigation Efficiency
5/17	3212.30	530.62	0.16
5/24	5327.38	624.92	0.12
5/31	5926.59	820.16	0.14
6/7	6236.11	930.88	0.15
6/14	6119.05	835.54	0.14
6/21	5793.65	769.24	0.13
6/28	5220.24	1046.72	0.20
7/5	3964.29	869.21	0.22
7/12	3599.21	679.10	0.19
7/19	3976.19	845.67	0.21
7/26	4839.29	804.63	0.17
8/2	3892.86	976.69	0.25
8/9	3261.90	835.54	0.26
8/16	3001.98	594.22	0.20
8/23	3214.29	635.86	0.20
8/30	2865.08	589.76	0.21
9/6	2615.08	438.69	0.17
9/13	2531.75	362.75	0.14
9/20	2450.40	425.70	0.17
9/27			

The mean irrigation efficiency, $\overline{X}_1 = 0.18$

The standard deviation, $\sigma_1 = 0.04$

Table 7-11 Weekly Irrigation Efficiencies for 1976 for the Wood River Valley Irrigation District No. 45

Beginning Date	Irrigation Diversions (ac-ft)	ET (ac-ft)	Irrigation Efficiency
5/17	4303.56	754.20	0.18
5/24	5152.78	812.32	0.16
5/31	5567.46	866.49	0.16
6/7	5902.78	814.55	0.14
6/14	5390.88	958.81	0.18
6/21	4674.61	1276.14	0.27
6/28	4909.52	1354.57	0.31
7/5	3833.32	1019.15	0.27
7/12	3515.86	752.92	0.21
7/12	3226.19	945.00	0.29
7/26	2676.58	958.01	0.36
8/2	2783.73	832.39	0.30
8/9	2156.75	724.88	0.34
8/16	2515.88	544.40	0.22
8/23	2525.80	723.19	0.29
8/30	2073.42	795.65	0.38
9/6	2222.21	488.94	0.22
9/13	2335.32	235.52	0.10
9/20	2384.92	368.47	0.16
9/27	The mean irrigation efficiency, $\bar{X}_2$= 0.24 The standard deviation, σ_2= 0.08		

Table 7-12 The Discrete Irrigation Efficiency Probability Density Functions for the Wood River Valley Irrigation District No. 45

Irrigation Efficiency Range	Irrigation Efficiency Regime	States of Nature (θ_k)	Probability of Occurrence ($P\theta_k$)
0.0-0.10	very low	θ_1	0.08
0.10-0.15	low	θ_2	0.16
0.15-0.20	moderately low	θ_3	0.26
0.20-0.25	marginal	θ_4	0.26
0.25-0.30	fair	θ_5	0.16
0.30-0.35	moderately high	θ_6	0.06
0.35-0.40	high	θ_7	0.02
0.40-0.45	very high	θ_8	0.00
			$\Sigma P\theta_k = 1.00$

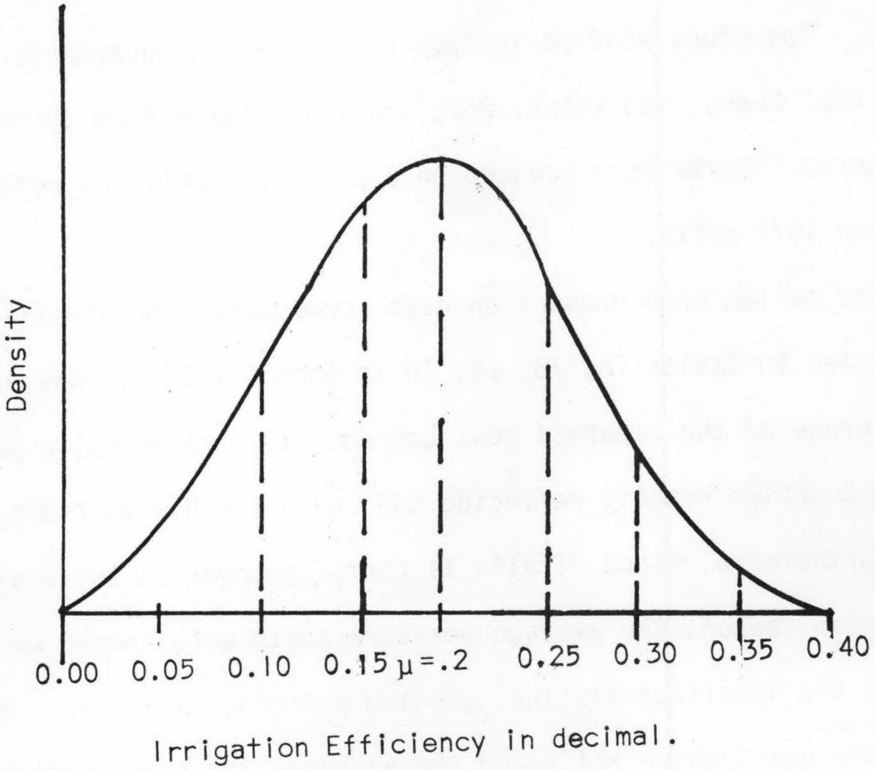

Fig.7-9 Selected Irrigation Efficiency Intervals for the Wood River Valley Irrigation District No.45.

7.3.4 DEVELOPMENT OF THE IRRIGATION CROP PRODUCTION COST FUNCTIONS

The irrigation crop production cost functions employed in this study were developed using unpublished data from the Department of Agricultural Economics of the University of Idaho. The department conducted a series of farm budget studies for some major crops in Benewah County, Jerome County, Twin Falls County, and the Boise Valley. The crops studied include alfalfa, hay, sugarbeets, potatoes, commercial beans, and wheat. Both small and large farm systems were considered. Costs were reduced on a per acre basis and reflected 1976 and 1977 costs.

Irrigation crop production cost components for alfalfa are summarized in Tables 7A, 7B, 7C, 7D in Appendix A. It was assumed that the average of the separate cost components for Twin Falls and Jerome Counties roughly reflected the costs for Blaine County.

Furthermore, since alfalfa is normally harvested twice within an irrigation season, the average per-acre costs were shared equally between the specified distinct growing periods, P1 and P2. However, since the costs shown reflected the expenses for three cuttings, they were adjusted downwards for the two cuttings obtainable in District 45. Adjusted costs used in the model are shown in Table 7-13.

The irrigation crop production costs for the wheat and alfalfa crop combination are shown in Table 7-14. The data in Table 7-15 represent a weighted cost. Computation was based on the assumption that the per-acre total cost burden for the system would be borne in proportion to the crop distribution of 60 percent for alfalfa and 40 percent for wheat. Furthermore, half of the per-acre cost burden was charged to each period P1 and P2. The actual cost input into the model for the Phase III investigation is shown in Table 7-16.

Table 7-13 Irrigation Crop Production Costs for Blaine County based on Twin Falls and Jerome Counties Cost Average

Cost category	Seasonal Cost (dollars/acre)	Period Cost (dollars/acre)
Operating inputs	28.13	14.03
Capital cost	8.50	4.25
Ownership cost	11.81	5.91
Labor cost	9.27	4.64
Total cost per acre	57.71	28.87

Table 7-14 Irrigation Crop Production Costs for Wheat and Alfalfa in Dollars Per Acre

Cost Category	Crop	
	Wheat	Alfalfa
Operating inputs	77.62	35.15
Capital cost	12.18	8.34
Ownership cost	16.89	8.84
Labor cost	9.27	13.28
Total cost (dollars/acre)	115.96	65.61

Table 7-15 Irrigation Crop Production Costs for Combined Wheat and Alfalfa in Dollars Per Acre[1/]

Cost Category	Crop		
	Wheat	Alfalfa	Alfalfa/Wheat
Operating inputs	31.05	21.09	52.14
Capital cost	4.87	5.00	9.87
Ownership cost	6.76	5.30	12.06
Labor cost	3.71	7.97	11.68
Total cost	46.39	39.36	85.75

1/ Computation is based on the crop distribution of 60% alfalfa and 40% of wheat.

Table 7-16 Irrigation Crop Production Costs for Combined Wheat and Alfalfa in Dollars Per acre per period [a]

Cost Category	Crop (Alfalfa/Wheat)
Operating inputs	26.07
Capital cost	4.94
Ownership cost	6.03
Labor cost	5.84
Total cost (dollars/acre)	42.88

[a] Computed on the basis that half of the cost in each category is charged to each of the two periods, P1 and P2

7.3.4.1 CROP INCOME

From the same unpublished reports by the Department of Agricultural Economics, the crop prices per ton of alfalfa and per bushel of wheat were \$45 and \$3.40, respectively. These were the prices farmers in the Jerome and Twin Falls Counties received for their alfalfa and wheat in 1976 and 1977. The crop pricing was used in the model assuming that it essentially remained fixed for Blaine County. Alfalfa yield per acre per cutting was 2 tons and an average per acre yield of wheat was 45 bushels.

As the model was designed to make an optimal irrigation decision at the end of each period, an action-state monetary payoff matrix must be generated during each period.

Since wheat is not normally harvested in mid-July, and some monetary function must be developed for the period, a technique was borrowed for determining what proportion of the total seasonal harvest or yield would be attributed to the periods, P1 and P2. The technique developed by Salter and Goode (1967) and used by Conklin and Schmisseur (1976) was modified and used. The modified version becomes:

$$Y_{ijk} = \sum_{S=1}^{m} \left[(\text{Growth}) (\lambda'_{ijk}) (Y_{max}) \right] \qquad (7\text{-}2)$$

where:

Y_{ijk}, λ'_{ijk} and Y_{max} are described in Section 6.5.2.1

Growth = crop yield coefficient for period, S, and crop, j. The seasonal yield coefficients developed by Conklin and Schmisseur (1976) for the typical crops in Oregon are given in Table 7E in Appendix A. Based on the data, 0.90 and 0.1 were the coefficients for wheat, selected for the periods P1 and P2, respectively.

7.3.4.2 IRRIGATION WATER USE ASSESSMENT COST

In the Irrigation District No. 45, water does not have a cost per se. Instead, a charge is seasonally assessed for using water. The deficit in the Irrigation District's balance sheet is what is usually shared among the stockholders. Table 7F in appendix A shows a typical balance sheet for 3 fiscal years in the district. The figures in Table 7-17 show the 1976 and 1977 irrigation season water assessments that are dependent upon water rights. A $1.50 per acre foot charge for irrigation water was the flat assessed rate assumed.

Table 7-17 Water Assessment Cost for the Wood River Irrigation District No. 45, for 1976-1977[1/]

Water Right	Charge/ miners inch	Charge/ acre-ft	Charge/ Cfs
1883 and older	$0.067	$1.69	$3.35
1884-1885	$0.062	$1.57	$3.10
1886-	$0.060	$1.52	$3.0
1887-1891	$0.056	$1.41	$2.8
1902	$0.031	$0.78	$1.55

[1/] Source is Jim Eakin, The Wood River Valley Irrigation District #45.

7.3.5 CROP RESPONSE FUNCTIONS

The problems and large uncertainties associated with obtaining and actually employing a crop response function are described in Section 6.4.4.1.

Within the range where soil moisture deficits are distributed throughout the season in a manner limiting evapotranspiration, Jensen (1977) suggested that a linear response is an adequate relationship between crop yield and water. However, when water is applied at increasing levels, assumption of a curvilinear function is not uncommon.

As crop response functions for alfalfa or wheat were not found to be published, three synthetic crop functions were developed and used. They represent the three most frequently postulated crop response curve shapes in published literature. A mathematical function or equation has been fitted to each curve. Each crop response function took title from the type of equation fitted to it. A linear type, an exponential type, and a curvilinear or polynomial type crop response were thus envisaged as shown in Figures 7-10, 7-11, and 7-12.

For each response, it was assumed that irrigation application in excess of crop requirement would result in no decline in yield; that is, no penalty function was established for excessive irrigation. The other assumption was that whatever irrigation water supply was available would be used to uniformly irrigate the entire cropped acreage. The synthetic crop functions would generate the extent of yield penalties for under irrigation.

7.3.6 DEVELOPMENT OF A UTILITY FUNCTION FOR THE WOOD RIVER VALLEY IRRIGATION DISTRICT NO 45.

Ideally, a utility function that uniquely reflects the general

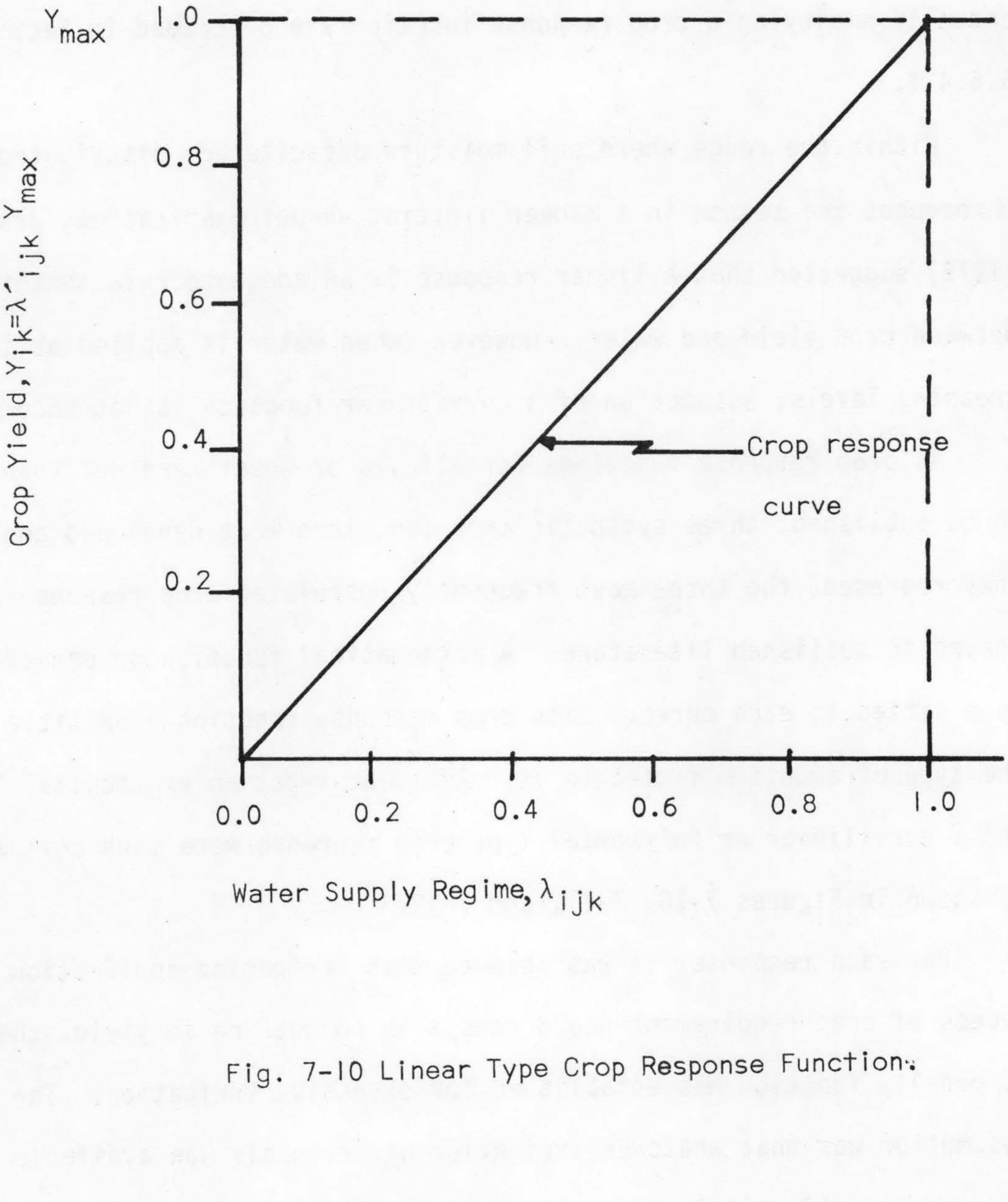

Fig. 7-10 Linear Type Crop Response Function.

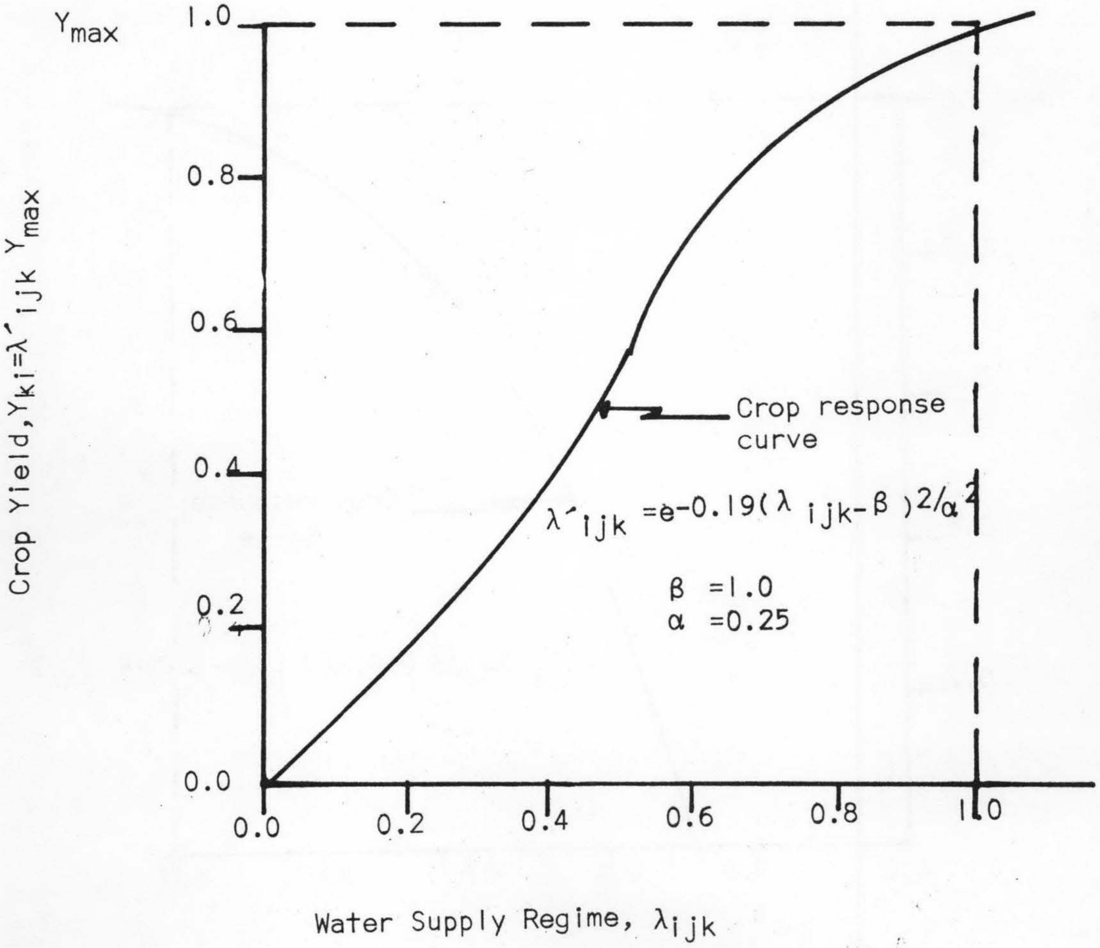

Fig. 7-11 Exponential Type Crop Response Function.

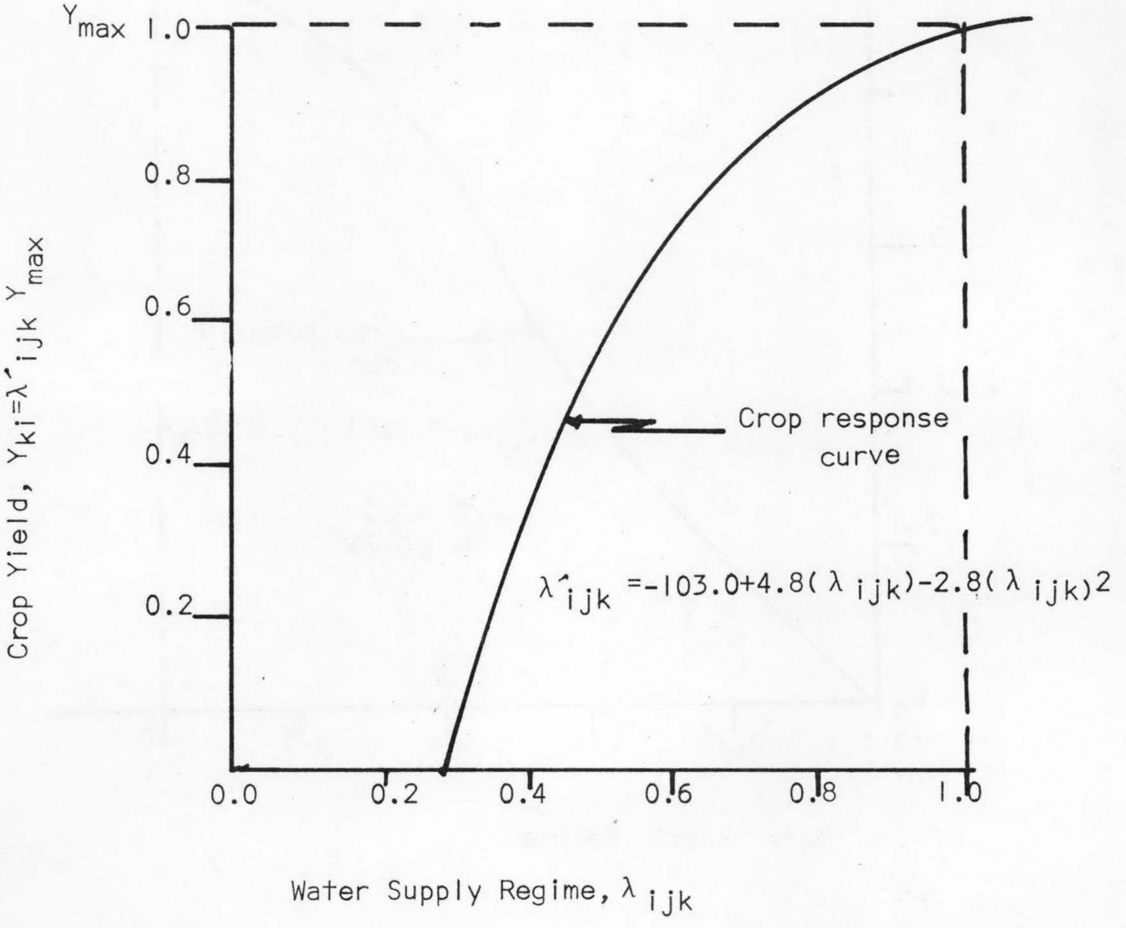

Fig. 7-12 Polynomial Type Crop Response Function.

response characteristics of farmers toward risk should be derived. Such a detailed exercise would, however, require extensive investments in time and money, and could sometimes be extremely difficult. Schlaifer (1959) and Officer and Halter (1968) presented the methodology and associated communication problems for questioning people to obtain their utility functions.

As a utility function is characteristically dependent upon such variable factors including person, time, and wealth, effort was not made in developing it for this study. Individuals have demonstrated a rather erratic and inconsistent response when confronted with hypothetical risky situations rather than real ones.

However, as the author was hypothetically operating as a hired professional engineer for the farmers, ethically dedicated and obligated to developing optimal designs for his clients, his utility function was used. This does not, however, imply that the utility function for the author is equivalent to that for the farmers.

A computer routine was written to generate a series of action-state terminal monetary payoffs. Using the established N-M procedure described in section 6.4.4.3., a utility function was derived (Figure 7-13), and then input into another computer routine separately developed for the model Phases I, II, and III. As the expected monetary value, EMV, was another objective criterion considered, linearity of utility and monetary payoffs was assumed (Figure 7-14).

7.4 DESCRIPTION OF THE COMPUTER PROGRAM

Data and information collection and generation, data analyses and optimality search represent the sequential stages in the decision theory optimization model. The flow chart shown in Figure 7-15 displays in

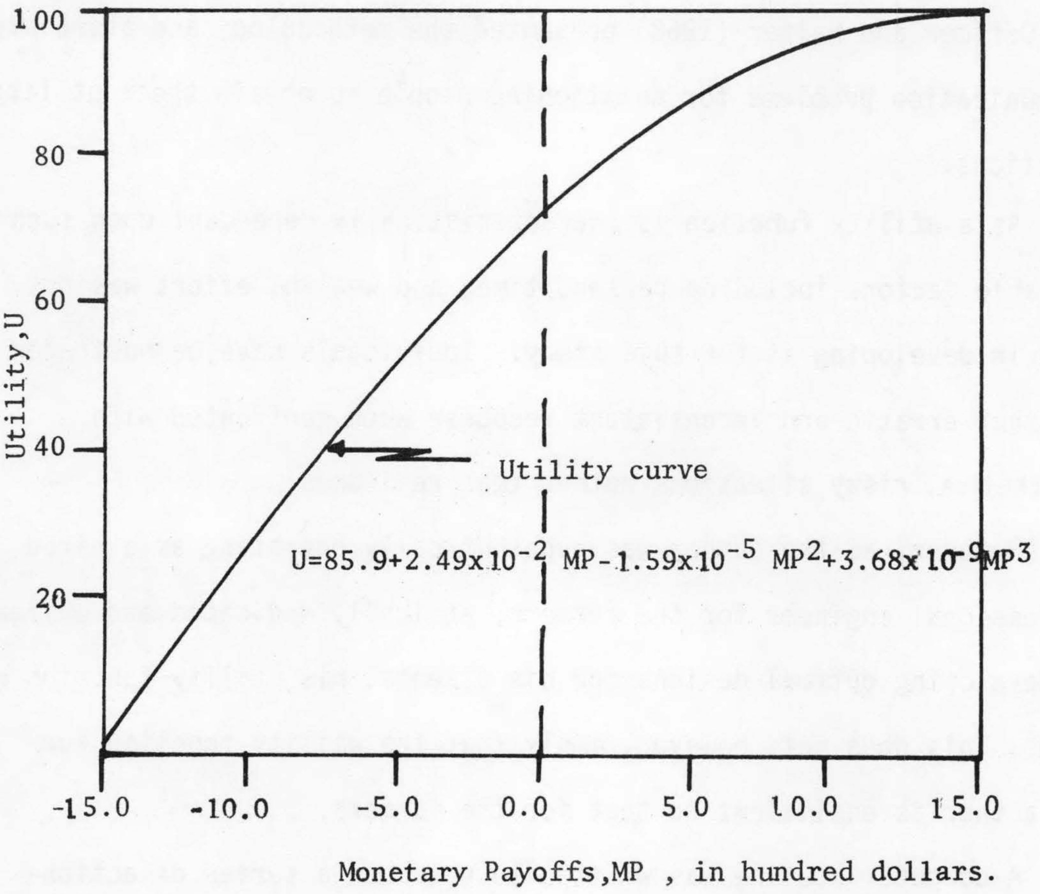

Fig.7-13 Utility Function for The Wood River Valley Irrigation District No.45

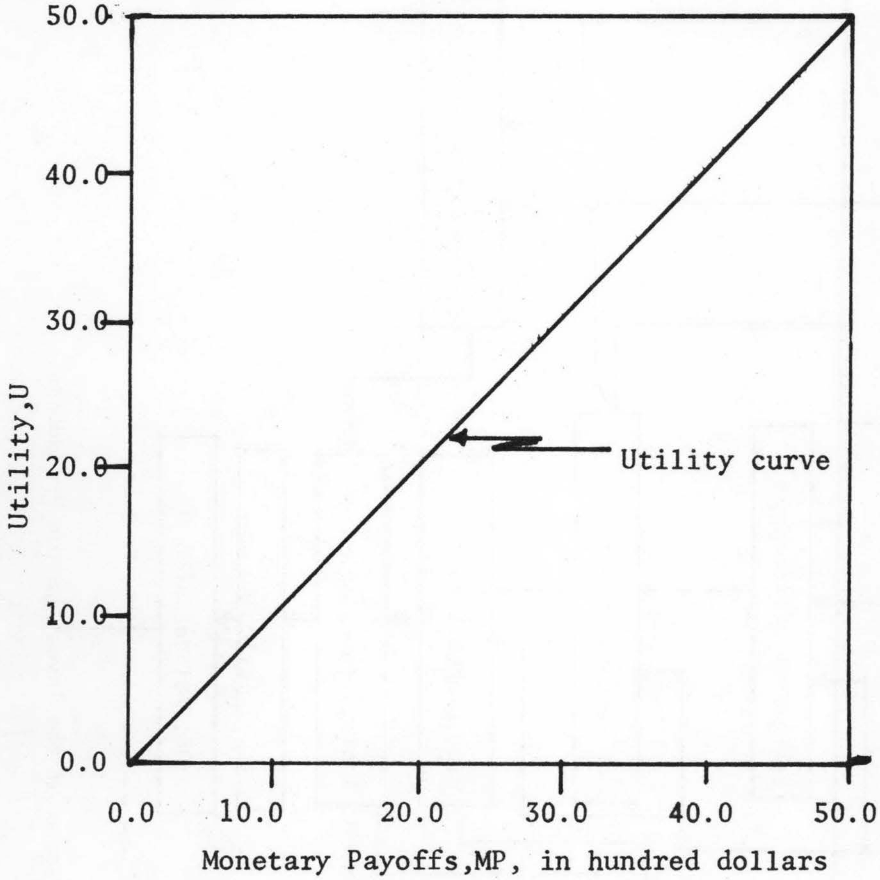

Fig.7-I4 A Linear Utility Function for The Wood River Valley Irrigation District No.45

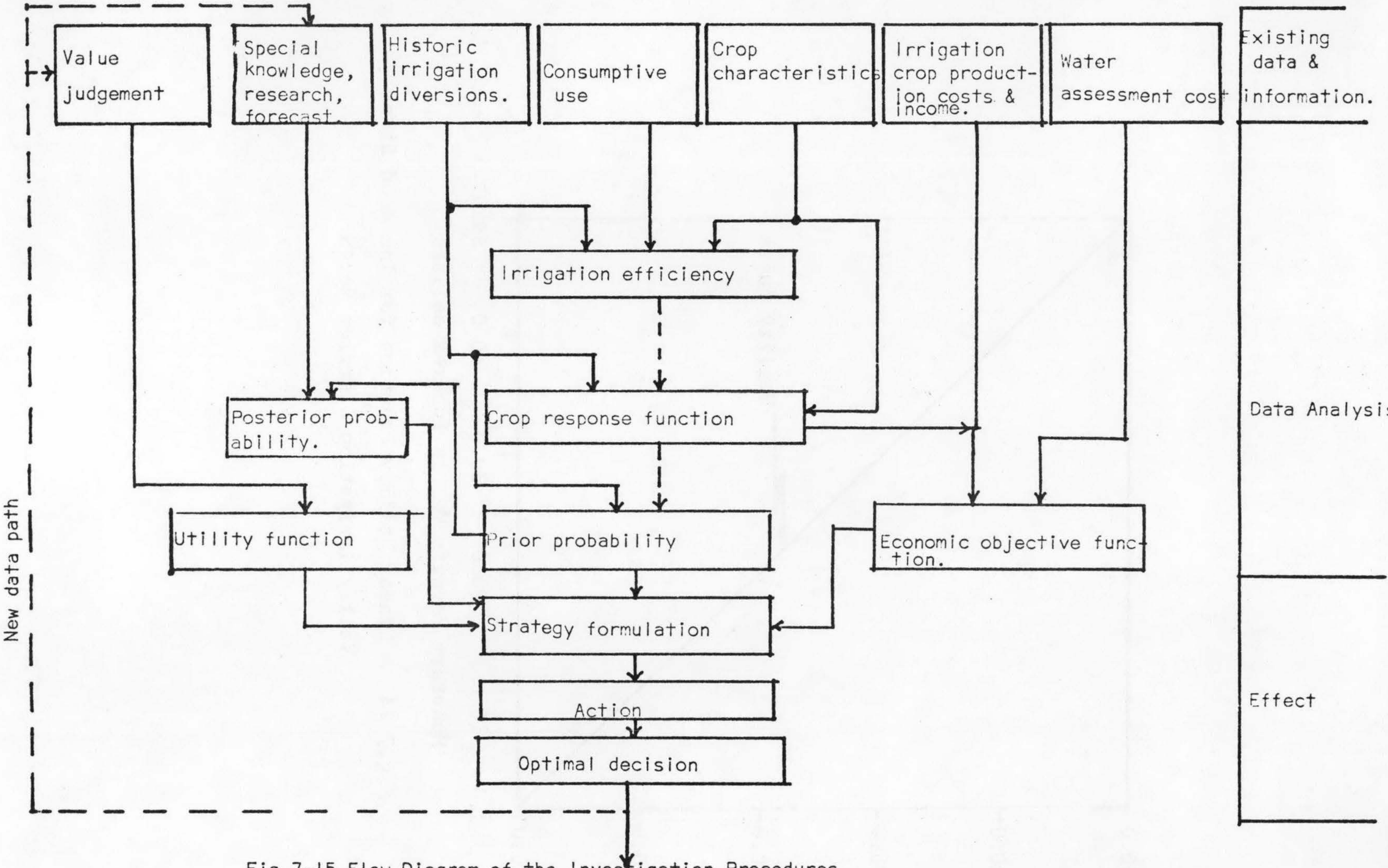

Fig.7-15 Flow Diagram of the Investigation Procedures.

detail, the various decision processes that were involved. The computer routine developed separately for the single crop and multi-crop systems requires data for any specified irrigation period, and generates an optimal strategy for that period. Both the expected monetary value, EMV, and the expected utility, EU, were used as the decision strategy criteria. The computer listings are documented in Appendix B.

CHAPTER VIII

RESULTS

8.1 MODEL OUTPUTS

The Bayesian decision theory optimization model developed to conjunctively consider the hydrologic and irrigation efficiency events as probabilistic input parameters was applied to the Wood River Valley Irrigation District No. 45. The delineated study phases were described in Section 7.2, and the optimal strategy for each phase is described in Sections 8.1.1, 8.1.2, and 8.1.3.

8.1.1 MODEL OUTPUT: PHASE I STUDY

The computed overall mean and maximum irrigation efficiency values for the Wood River Valley Irrigation District system were 20 percent and 40 percent, respectively.

A 20 percent deterministic irrigation efficiency was first input into the model. Model output, specifying the optimal areas to be irrigated at different periods, the maximum expected utilities, EU, and the maximum expected monetary values, EMV, yielding the optimal areas, is shown in Table 8-1. Both the expected utility and expected monetary value decision criteria yielded the same optimal decision strategy. That is, the same optimal areas to be irrigated were predicted during each period, regardless of the decision criterion.

However, when 40 percent certainty irrigation efficiency was considered, greater optimal areas to be irrigated, higher maximum expected utilities, and maximum expected monetary values were generated for both periods (Table 8.2). At 40 percent irrigation efficiency over 9000 acres could be optimally irrigated regardless of the

Table 8-1 Optimal Alfalfa Acreages to Irrigate at 20 Percent Irrigation Efficiency: An Exponential Type Crop Response Function

	Maximum Expected Utility EU, Decision Criterion		Maximum Expected Monetary Value, EMV, Decision Criterion	
Irrigation Period	EU	Optimal Acreage	EMV$\times10^{-4}$	Optimal Acreage
P1	90.13	6000	20.10	6000
P2	88.09	4000	10.10	4000
PT	92.18	5000	33.60	5000

Table 8-2 Optimal Alfalfa Acreages to Irrigate at 40 Percent Irrigation Efficiency: An Exponential Type Crop Response Function

	Maximum Expected Utility EU, Decision Criterion		Maximum Expected Monetary Value, EMV, Decision Criterion	
Irrigation Period	EU	Optimal Acreage	EMV$\times10^{-4}$	Optimal Acreage
P1	93.62	over 10,000	42.60	over 10,000
P2	90.19	9,000	23.60	9,000
PT	96.21	over 10,000	75.90	over 10,000

decision criterion adopted and the irrigation period considered. This indicates that irrigation diversions were, at all times, actually more than adequate for the irrigated crop, assuming the system efficiency was 40 percent. The optimal areas generated using the expected monetary value decision criterion were higher than using the expected utility criterion.

From the results, it clearly follows that the optimal decision strategy was dependent upon the deterministic value assumed for the irrigation efficiency. The higher the efficiency selected for the system, the greater the optimal area to be irrigated and the associated maximum expected benefits.

8.1.2 MODEL OUTPUT: PHASE II STUDY

The parameter inputs into the Phase II model were described in Section 7.2 to include probabilistic irrigation diversions, probabilistic irrigation efficiency, a single crop system and three crop response functions.

8.1.2.1 OPTIMAL STRATEGY USING THE EXPECTED UTILITY, EU, DECISION CRITERION

The optimal acreages to be irrigated at different periods, and the associated maximum expected utilities, EU, yielding the optimal areas are shown in Table 8-3. By assuming either a linear type or an exponential type crop response function, the same optimal acreages to be irrigated during the different periods and essentially equal maximum expected utilities, EU, yielding the optimal acreages, were predicted. This result indicates that the linear type crop function could be a good approximation of the exponential type function. Greater optimal areas and maximum expected utilities were predicted during the periods P1 and PT, using the polynomial type crop response than using both the linear and exponential type crop response functions. Predictions remained essentially the same during the period, P2, regardless of the crop response function assumed.

8.1.2.2 OPTIMAL STRATEGY USING THE EXPECTED MONETARY VALUE, EMV, DECISION CRITERION

The model output using the expected monetary value decision criterion shown in Table 8-4 confirmed that a linear type crop response could be a good approximation of an exponential type crop response function. Both functions predicted the same optimal acreages to be irrigated at the different periods, and almost equal maximum expected

Table 8-3 Optimal Acreages to Irrigate at Different Periods, Under a Normal Distribution Assumption for Irrigation Efficiency: Expected Utility, EU, Criterion

	Irrig. Period, P1		Irrig. Period, P2		Irrig. Period, PT	
Crop Response Function	Max. EU	Optimal Acreage	Max. EU	Optimal Acreage	Max. EU	Optimal Acreage
Linear	89.38	5000	87.87	4000	91.31	4000
Exponential	89.51	5000	87.88	4000	91.45	4000
Polynomial	90.38	6000	88.06	4000	92.52	5000

Table 8-4 Optimal Acreages to Irrigate at Different Periods, Under a Normal Distribution Assumption for Irrigation Efficiency: Expected Monetary Value, EMV, Criterion

	Irrig. Period, P1		Irrig. Period, P2		Irrig. Period, PT	
Crop Response Function	Max. EMV $\times 10^{-4}$	Optimal Acreage	Max. EMV $\times 10^{-4}$	Optimal Acreage	Max. EMV $\times 10^{-4}$	Optimal Acreage
Linear	16.40	6000	9.10	4000	28.40	5000
Exponential	17.20	6000	9.20	4000	29.70	5000
Polynomial	22.10	7000	10.60	5000	37.80	6000

monetary values. The polynomial type crop response function consistently predicted greater optimal acreages and maximum expected monetary values than both the linear and the exponential crop functions.

Generally, the optimal areas to be irrigated at different periods were higher using the expected monetary value decision criterion than using the expected utility criterion, as the effects of risk response began reflecting on the optimal decision strategy (Table 8-3, 8-4).

8.1.3 MODEL OUTPUT: PHASE III STUDY

The only difference between Phase II and Phase III is that, while Phase II considered a single crop system, Phase III examined a multi-crop system - wheat and alfalfa.

8.1.3.1 OPTIMAL STRATEGY USING THE EXPECTED UTILITY, EU, CRITERION

The optimal acreages to be irrigated at different periods and the maximum expected utilities yielding the optimal areas are listed in Table 8-5. Here again, both the linear and the exponential type crop response functions predicted the same optimal decision strategy, that is, equal optimal areas and maximum expected utilities during each period. Assuming a polynomial type crop function, greater optimal areas and maximum expected utilities were obtained than using either the linear or the exponential type crop function.

In comparing the single and the multi-crop models, both predicted equal optimal areas during the period, PT. Higher optimal areas were obtained for the multi-crop system than for the single crop system during the period, P1. However, the optimal areas dropped dramatically under a multi-crop system during the period, P2 (Table 8-3, 8-5). The sharp drop was due to the impact of the seasonal crop yield coefficient

Table 8-5 Optimal Acreages to Irrigate at Different Periods, Under a Normal Distribution Assumption for Irrigation Efficiency: Expected Utility, EU, Criterion

	Irrig, Period, P1		Irrig, Period, P2		Irrig, Period, PT	
Crop Response Function	Max. EU	Optimal Acreage	Max. EU	Optimal Acreage	Max. EU	Optimal Acreage
Linear	90.50	6000	85.66	2000	89.67	4000
Exponential	90.62	6000	85.66	2000	89.82	4000
Polynomial	91.88	7000	87.24	5000	90.25	5000

Table 8-6 Optimal Acreages to Irrigate at Different Periods Under a Normal Distribution Assumption for Irrigation Efficiency: Expected Monetary Value, EMV, Criterion

	Irrig. Period, P1		Irrig. Period, P2		Irrig. Period, PT	
Crop Response Function	Max. EMV $x10^{-4}$	Optimal Acreage	Max. EMV $x10^{-4}$	Optimal Acreage	Max. EMV $x10^{-4}$	Optimal Acreage
Linear	22.50	6000	-1.00	2000	18.40	5000
Exponential	23.40	6000	-1.00	2000	19.60	5000
Polynomial	32.70	8000	9.80	7000	26.10	6000

values that highly favored the period, P1, more than the period, P2. The importance of the yield coefficient as a decision variable is demonstrated. The plots in Figures 8-1, 8-2, and 8-3 show variation in EU for different areas to be irrigated. The peak EU shown determines the optimal area to be irrigated.

8.1.3.2 OPTIMAL STRATEGY USING THE EXPECTED MONETARY VALUE, EMV CRITERION

The data listed in Table 8-6 show the optimal acreages to be irrigated at different periods and the maximum expected monetary value associated with the optimal areas. Again, no significant difference existed in the optimal stretegy generated using either the linear or the exponential type crop response functions. The polynomial type crop response again consistently yielded greater optimal areas and maximum expected monetary values than the other crop functions.

When both the linear and the exponential crop response functions were assumed, negative expected monetary values were obtained during the period P2. This implies that if either the linear or the exponential crop response were the actual function, it would be an economically poor management decision to irrigate during this period. It would however, be economically beneficial to irrigate at this period, only if the polynomial function actually reflected the crop yield and water relationship. Thus, the type of crop response function was shown to impact optimal decision strategy. The plots in Figures 8-4, 8-5, 8-6 show the relationships between EMV and irrigated area.

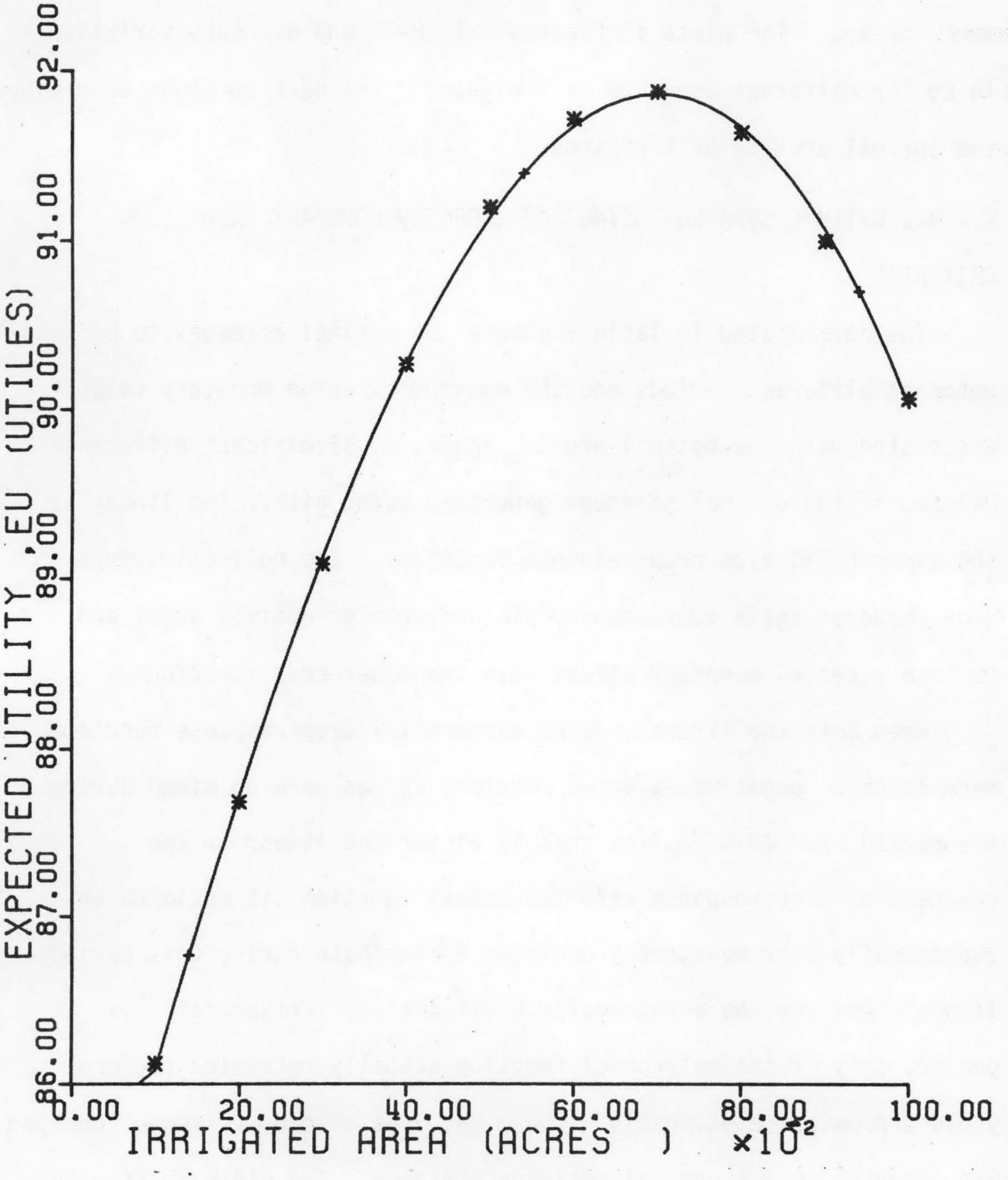

Fig.8-I Expected Utility-Irrigated Area Curve,for Period PI:
A Polynomial Crop Response Function for a Multi-crop System.

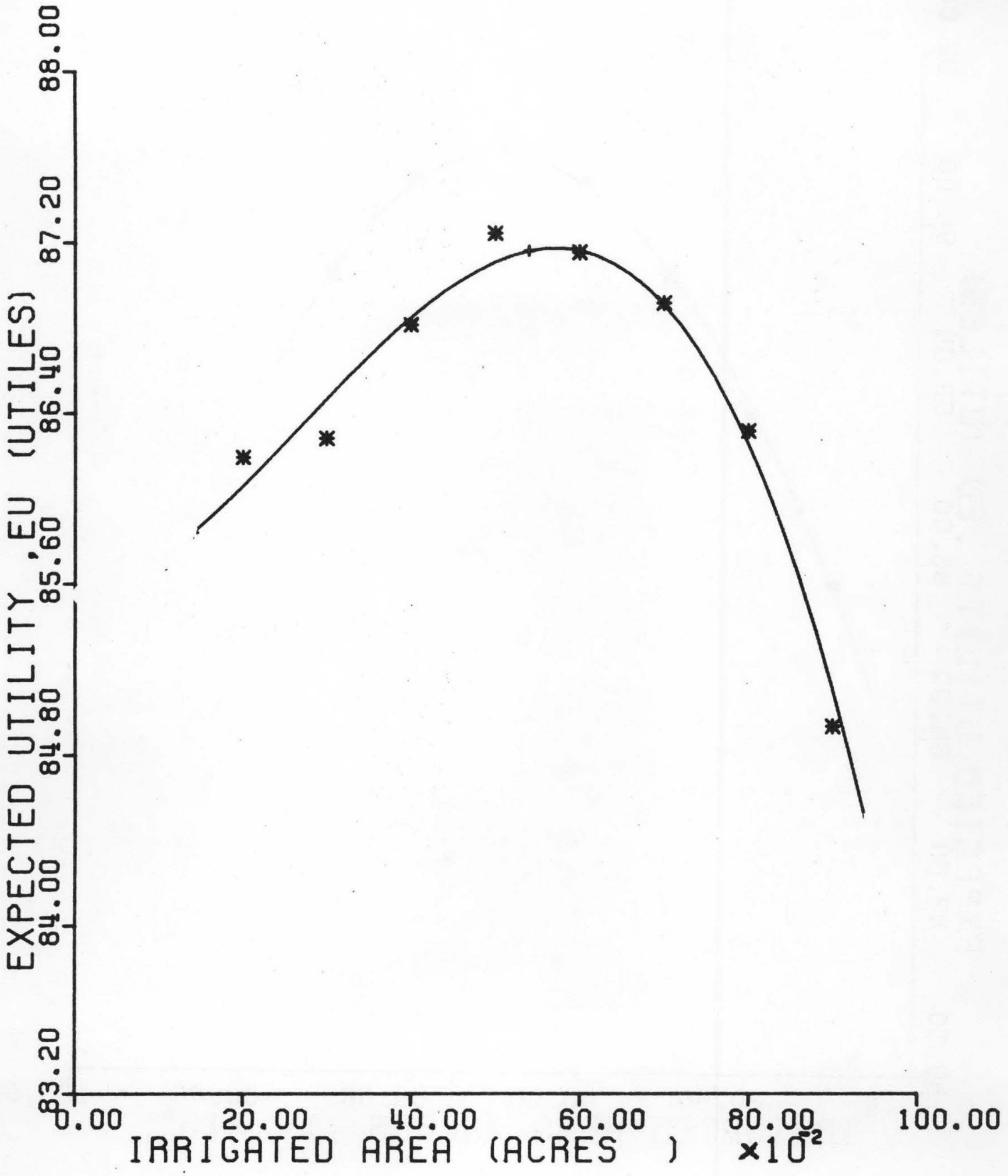

Fig.8-2 Expected Utility-Irrigated Area Curve, for Period P2:

A Polynomial Crop Response Function for a Multi-crop System

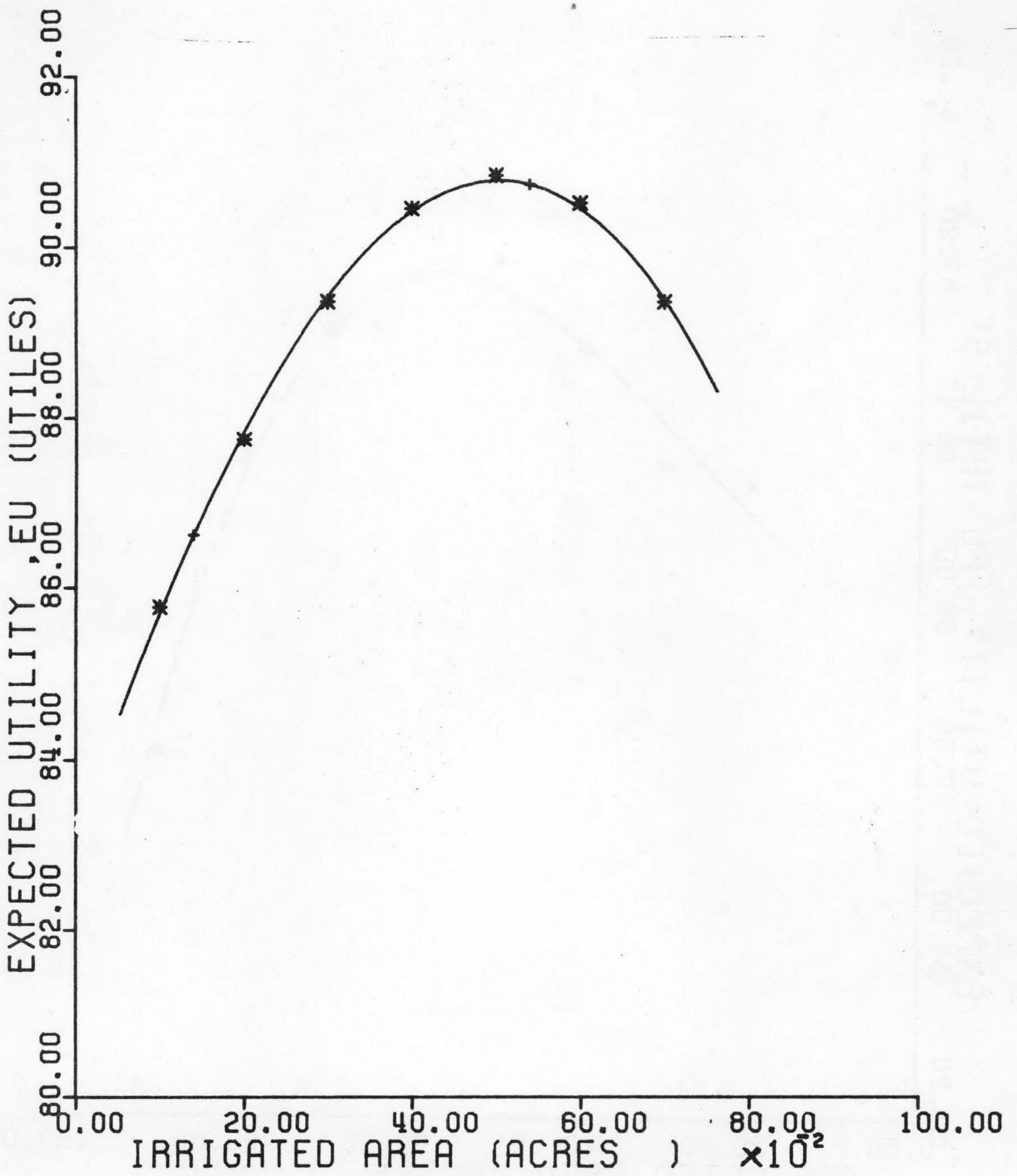

Fig.8-3 Expected Utility-Irrigated Area Curve, for Period PT:

A Polynomial Crop Response Function for a Multi-crop System.

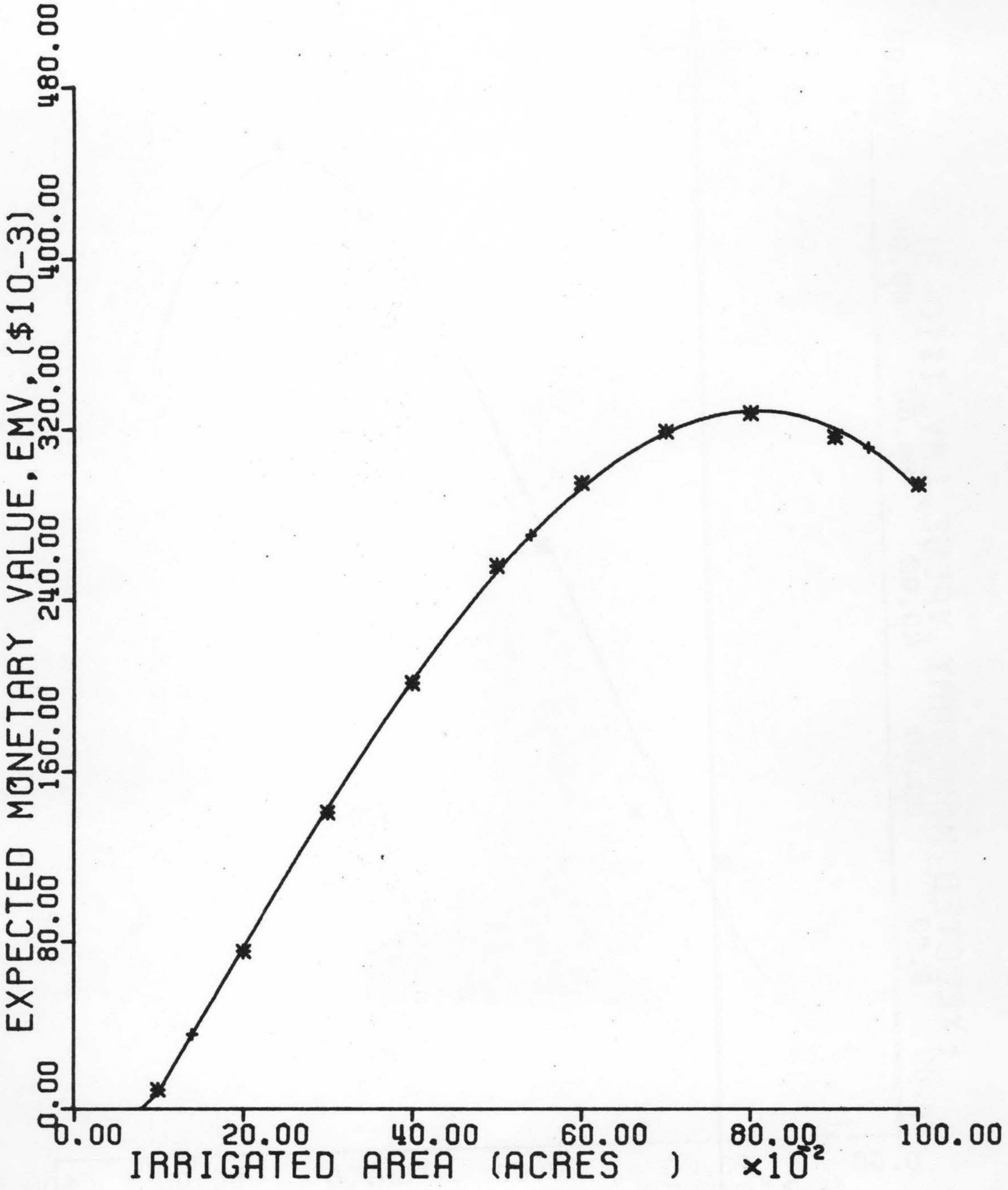

Fig.8-4 Expected Monetary Value-Irrigated Area Curve, for Period PI: A Polynomial Crop Response Function for a Multi-crop System.

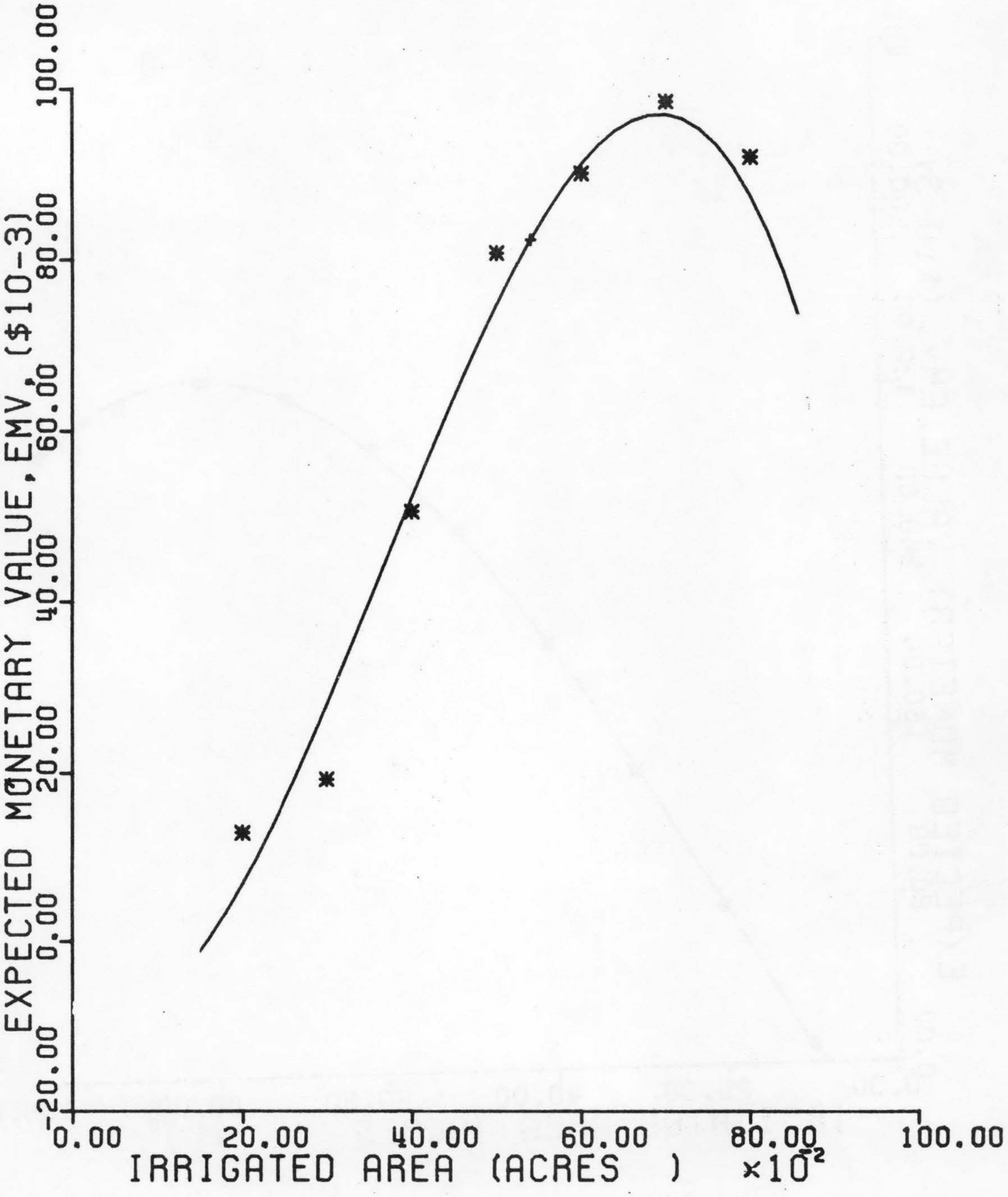

Fig.8-5 Expected Monetary Value-Irrigated Area Curve, for Period P2: A Polynomial Crop Response Function for a Multi-crop System.

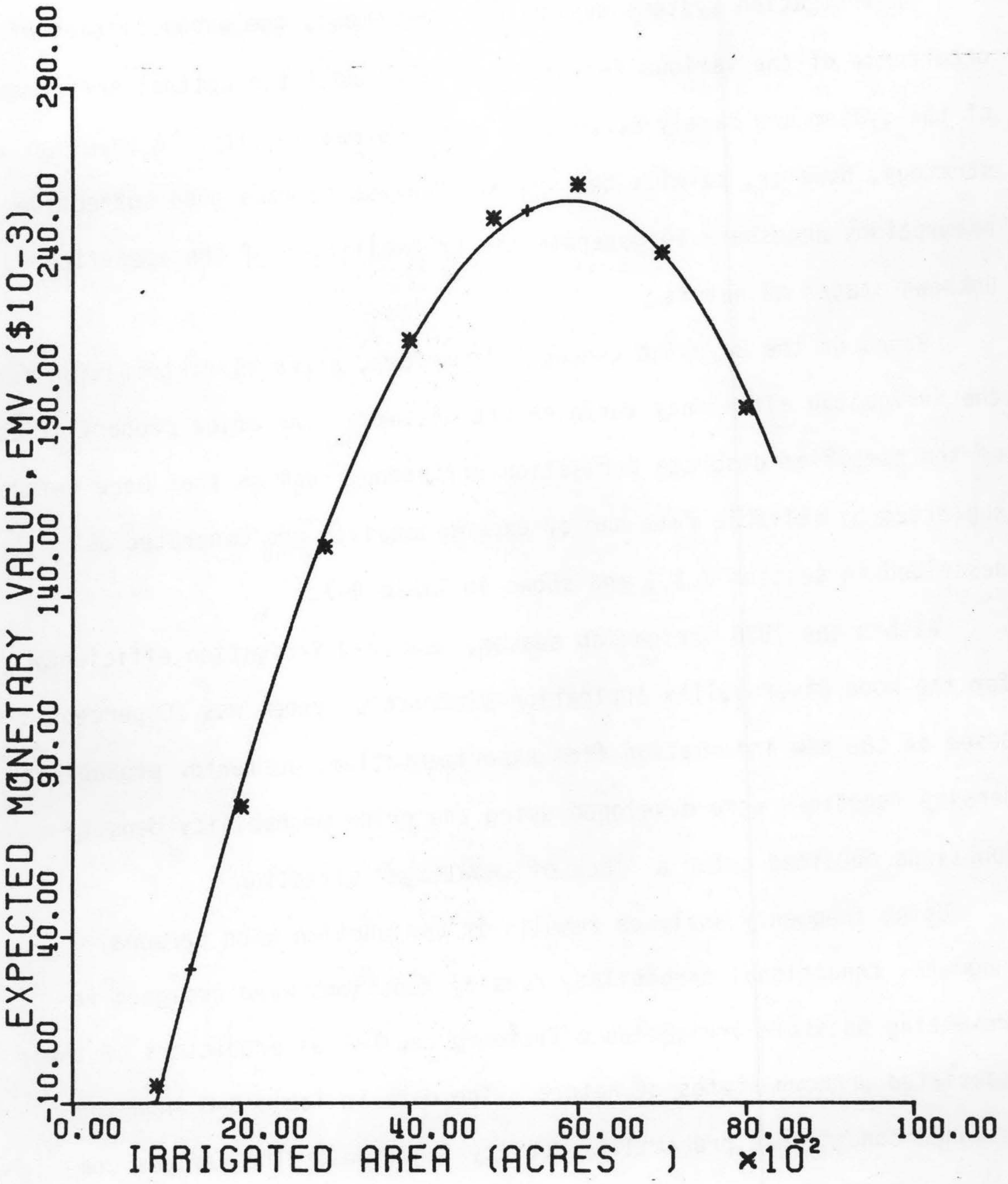

Fig.8-6 Expected Monetary Value-Irrigated Area Curve for Period PT: A Polynomial Crop Response Function for a Multi-crop System.

8.1.4 BAYESIAN DECISION STRATEGY

In irrigation systems design and management, the probabilities of occurrence of the various factors that can impact the optimal performance of the system are rarely known with complete reliability. A Bayesian strategy, however, permits the systems analyst to make good subjective assumptions necessary to generate the probabilities of the specified unknown states of nature.

Based on the Bayesian concept, therefore, a normal distribution for the irrigation efficiency variates was assumed. The prior probabilities of the specified discrete irrigation efficiency regimes that were neither supported by reliable data nor by experimentation are generated as described in section 7.3.3 and shown in Table 8-7.

Within the 1976 irrigation season, measured irrigation efficiency for the Wood River Valley Irrigation District's system was 20 percent. Based on the new information from experimentation, posterior probability density functions were developed using the prior probability density functions obtained under a "lack of knowledge" situation.

Using frequency analyses results in conjunction with personal judgment, conditional probability density functions were assigned representing possible irrigation efficiency regimes as predictors of their associated unknown states of nature. The data in Table 8-8 show the assigned conditional probability density functions. The various components of the Bayes' equation 6-25 were computed as shown in Table 8-9 yielding the updated, and the refined posterior probability density functions shown in Table 8-10. These probabilities were input into the Phase III model.

Table 8-7 Prior Probability Density Functions for Irrigation Efficiency Events

State of Nature θ_k (Irrigation Efficiency)	Prior Probability $P(\theta_k)$
θ_1 : 5%	0.08
θ_2 : 12.5%	0.16
θ_3 : 17.5%	0.26
θ_4 : 22.5%	0.26
θ_5 : 27.5%	0.16
θ_6 : 32.5%	0.06
θ_7 : 37.5%	0.02
θ_8 : 42.5%	0.00
	$\sum_{k=1}^{n} P(\theta_k) = 1.00$

Table 8-8 Conditional Probabilities of Irrigation Efficiencies as Predictors of the Unknown States of Nature

P(Irrig. eff/state)	State of Nature, θ_k, of Irrigation Efficiency							
Irrig. Efficiency	5%	12.5%	17.5%	22.5%	27.5%	32.5%	37.5%	42.5%
Z_1(favors 5%)	0.50	0.20	0.00	0.00	0.00	0.00	0.00	0.00
Z_2(favors 12.5%)	0.40	0.50	0.20	0.10	0.00	0.00	0.00	0.00
Z_3(favors 17.5%)	0.10	0.20	0.50	0.20	0.10	0.00	0.00	0.00
Z_4(favors 22.5%)	0.00	0.10	0.20	0.60	0.20	0.10	0.10	0.00
Z_5(favors 27.5%)	0.00	0.00	0.10	0.10	0.50	0.30	0.10	0.10
Z_6(favors 32.5%)	0.00	0.00	0.00	0.00	0.20	0.50	0.20	0.20
Z_7(favors 37.5%)	0.00	0.00	0.00	0.00	0.00	0.10	0.50	0.20
Z_8(favors 42.5%)	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.50
	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 8-9 Computing the $P(Z/\theta_k)$ Component of the Posterior Probabilities of the Irrigation Efficiency

$P(Z\theta_k)$ $P(\theta_k)$

$P(Z_4/\theta_1) \cdot P(\theta_1) = 0.00 \times 0.08 = 0.00$

$P(Z_4/\theta_2) \cdot P(\theta_2) = 0.10 \times 0.16 = 0.016$

$P(Z_4/\theta_3) \cdot P(\theta_3) = 0.20 \times 0.26 = 0.052$

$P(Z_4/\theta_4) \cdot P(\theta_4) = 0.60 \times 0.26 = 0.156$

$P(Z_4/\theta_5) \cdot P(\theta_5) = 0.20 \times 0.16 = 0.032$

$P(Z_4/\theta_6) \cdot P(\theta_6) = 0.10 \times 0.06 = 0.006$

$P(Z_4/\theta_7) \cdot P(\theta_7) = 0.10 \times 0.02 = 0.002$

$P(Z_4/\theta_8) \cdot P(\theta_8) = 0.00 \times 0.00 = \underline{0.000}$

$\sum_{L=1}^{n} P(Z_4/\theta_k)\, P(\theta_k) = 0.264$

Table 8-10 Computing the Posterior Probabilities When 20% Irrigation Efficiency was Measured

$(P\theta_k/Z_4)$

$P(\theta_1/Z_4) = 0.00/0.264 = 0.000$

$P(\theta_2/Z_4) = 0.016/0.264 = 0.061$

$P(\theta_3/Z_4) = 0.052/0.264 = 0.197$

$P(\theta_4/Z_4) = 0.156/0.264 = 0.590$

$P(\theta_5/Z_4) = 0.032/0.264 = 0.121$

$P(\theta_6/Z_4) = 0.006/0.264 = 0.023$

$P(\theta_7/Z_4) = 0.002/0.264 = 0.008$

$P(\theta_8/Z_4) = 0.00/0.264 = \underline{0.000}$

1.00

The results obtained adopting the Bayesian methodology for revising probability functions are shown in Table 8-11 and 8-12.

Table 8-11 Optimal Multi-Crop Acreages to Irrigate when 20 Percent Irrigation Efficiency was Measured: Expected Utility, EU, Criterion

	Irrig. Period, P1		Irrig. Period, P2		Irrig, Period, PT	
Crop Response Function	Max. EMV x10^{-4}	Optimal Acreage	Max. EMV x10^{-4}	Optimal Acreage	Max. EMV x10^{-4}	Optimal Acreage
Linear	26.70	7000	-0.50	3000	22.30	5000
Exponential	28.10	7000	-0.70	3000	23.80	6000
Polynomial	39.60	9000	15.80	8000	31.60	7000

Table 8-12 Optimal Multi-Crop Acreages to Irrigate when 20 Percent Irrigation Efficiency was Measured: Expected Monetary Value, EMV, Criterion

	Irrig. Period, P1		Irrig. Period, P2		Irrig. Period, PT	
Crop Response Function	Max. EU	Optimal Acreage	May. EU	Optimal Acreage	Max. EU	Optimal Acreage
Linear	91.19	7000	85.73	3000	90.44	5000
Exponential	91.36	7000	85.68	3000	90.63	5000
Polynomial	92.75	8000	87.80	6000	91.71	6000

Comparing the results in these tables with those obtained earlier under a "lack of knowledge situation" that is, using prior probability functions (Tables 8-5, 8-6), a more improved optimal strategy resulted due to the new information about the irrigation efficiency. That is, greater optimal areas, maximum expected utilities and maximum expected monetary values were obtained using the Bayesian strategy than using only prior knowledge, regardless of the decision criterion adopted and the irrigation period considered. Furthermore, the expected monetary losses that occurred in the period, P2, under a "no knowledge situation" reduced signficantly as a result of the new information through experimentation. The polynomial type crop response function continued to yield higher optimal strategy than the other functions. The expected monetary value criterion also persistently yielded higher optimal areas at different periods than the expected utility criterion.

8.2 POST OPTIMAL ANALYSES

The hydrologic and irrigation efficiency factors are not the only critical variable input parameters associated within irrigation system optimization. The values of other inputs including consumptive use, irrigation cost components, water assessment, seasonal crop yield coefficients, and others are not always known with certainty. Ideally, the probabilities of the occurrence of their specified values should be considered in the model.

The variability and inaccuracy of input data present serious problems in the development of a meaningful and realistic irrigation systems model. However, a post optimal analysis through a sensitivity analysis can reveal how optimality changes with a given variable input parameter. That is, it reveals the rate of change of the objective function with respect to the rate of change in the variable parameter of interest.

The sensitivity analysis was conducted on the Phase III model.

8.2.1 SENSITIVITY OF OPTIMAL STRATEGY TO VARIABILITIES IN IRRIGATION EFFICIENCY PROBABILITY DISTRIBUTION

8.2.1.1 LOG-NORMAL DISTRIBUTION ASSUMPTION FOR IRRIGATION EFFICIENCY VARIATES

Previously, a normal distribution postulate for irrigation efficiency was made. To test the sensitivity of the model to changes in the probability distribution, another postulate was made. That is, that the irrigation efficiency variates are log-normally distributed. This implies transforming all evaluated irrigation efficiency parameters to their log functions. Tests of skewness and kurtosis conducted on the transformed values showed a close approximation of the data to a normal distribution. The probability density functions from a log-normal distribution were determined and then input into the model.

Model output shown in Tables 8-13 and 8-14 when compared with that generated assuming a normal distribution (Tables 8-5, 8-6) indicated that the transformation of irrigation efficiency variates to a log function did not significantly change the optimal decision strategy. That is, the same optimal acreages to be irrigated at different periods and nearly equal maximum expected benefits were obtained using both probability distribution postulates.

Table 8-13 Optimal Acreages to Irrigate Under a Log-normal Distribution Assumption for Irrigation Efficiency: Expected Utility, EU, Criterion

	Irrig. Period, P1		Irrig. Period, P2		Irrig. Period, PT	
Crop Response	Max. EU	Optimal Acreage	Max. EU	Optimal Acreage	Max. EU	Optimal Acreage
Linear	90.59	6000	85.67	2000	89.73	4000
Exponential	90.71	6000	85.66	2000	89.87	5000
Polynomial	91.96	7000	87.23	5000	90.93	5000

Table 8-14 Optimal Acreages to Irrigate Under a Log-Normal Distribution Assumption for Irrigation Efficiency: Expected Monetary Value, EMV, Criterion

	Irrig. Period, P1		Irrig. Period, P2		Irrig. Period, PT	
Crop Response Function	Max. EMV $x10^{-4}$	Optimal Acreage	Max. EMV $x10^{-4}$	Optimal Acreage	Max. EMV $x10^{-4}$	Optimal Acreage
Linear	22.90	6000	-0.80	2000	18.90	5000
Exponential	23.80	7000	-0.90	2000	20.10	5000
Polynomial	33.40	8000	10.20	7000	26.70	6000

8.2.1.2 LAPLACE DISTRIBUTION ASSUMPTION FOR IRRIGATION EFFICIENCY VARIATES

Where data are lacking or doubts exist regarding the actual probability distribution of a stochastic event, equal probabilities can be assigned to the occurrence of the unknown states of nature associated with that event. This approach is known as the "principle of insufficient reason".

Adopting this concept, the eight states of nature for the irrigation efficiency regimes were assigned equal probabilities and the probabilities were then input into the model.

Model output in Tables 8-15, 8-16 shows greater optimal acreages to irrigate at different periods and higher maximum expected utilities and maximum expected monetary values than those determined using both the prior and posterior probability density functions.

Table 8-15 Optimal Acreages to Irrigate under a Laplace Distribution Assumption for Irrigation Efficiency: Expected Utility, EU, Criterion

	Irrig. Period, P1		Irrig. Period, P2		Irrig. Period PT	
Crop Response Function	Max. EU	Optimal Acreage	Max. EU	Optimal Acreage	Max. EU	Optimal Acreage
Linear	91.59	8000	85.87	3000	90.77	5000
Exponential	91.67	7000	85.87	2000	90.92	5000
Polynomial	92.86	8000	87.28	7000	91.90	6000

Table 8-16 Optimal Acreages to Irrigate under a Lapace Distribution Assumption for Irrigation Efficiency: Expected Monetary Value, EMV, Criterion

	Irrig. Period, P1		Irrig. Period, P2		Irrig. Period, PT	
Crop Response Function	Max. EMV $x10^{-4}$	Optimal Acreage	Max. EMV $x10^{-4}$	Optimal Acreage	Max. EMV $x10^{-4}$	Optimal Acreage
Linear	30.00	9000	-0.30	3000	25.20	6000
Exponential	30.80	9000	-0.40	3000	26.30	6000
Polynomial	40.30	9000	11.60	8000	33.80	7000

8.2.2 SENSITIVITY OF OPTIMAL STRATEGY TO UTILITY FUNCTION VARIABILITIES

Under similar model input parameters the optimal strategy was sensitive to the type of utility functions used. Model output indicated that the linear type utility function (EMV) consistently yielded greater optimal areas than the curvilinear function. The curvilinear function was actually the modeller's own utility. Brockway (1978) stated that a linear type utility function could most closely reflect the average utility function for farmers in the Wood River Valley Irrigation District No. 45. However, it would be desirable to institute a study to generate an irrigator utility function for the study area.

8.2.3 SENSITIVITY OF OPTIMAL STRATEGY TO CROP RESPONSE FUNCTION VARIABILITIES

Three crop response functions were considered. The linear type function was shown to be a good approximation of the exponential type function as both consistently yielded roughly the same optimal areas, and the same maximum expected utilities and maximum expected monetary values. Using the polynomial type function, greater optimal strategy than from both the linear and the exponential functions was consistently generated.

8.2.4 SENSITIVITY OF OPTIMAL STRATEGY TO WATER USE ASSESSMENT VARIABILITIES

The amount assessed for irrigation water use is a function of water rights and the irrigation district's annual budget deficits. In the sensitivity analysis, the dollars per acre-foot water assessment were allowed to vary between 1.5 to 8. For each increase in water assessment, the corresponding optimal decision strategy was generated, that is, the optimal acreage to irrigate and the associated maximum expected benefits.

Regardless of the amount assessed within the specified range, the same optimal areas were predicted. However, the associated maximum expected utilities and maximum expected monetary values declined as the assessed cost of water increased. That is, an inverse relationship exists between either the maximum expected utility or maximum expected monetary value and water assessment cost. Under the EMV and EU criteria, the constant optimal areas were 7000 and 5000 acres, respectively.

When 6.50 dollars were assessed, it became an economically poor decision to irrigate as the maximum expected monetary value was negative. The optimal acreage to irrigate was still 7000 acres. It could be implied that a 6 dollar water assessment cost would be the upper limit for the price of irrigation water in the study area.

8.2.5 SENSITIVITY OF OPTIMAL STRATEGY TO IRRIGATION CROP PRODUCTION COST COMPONENT VARIABILITIES

Farmers in the United States and the other parts of the world are presently facing escalating crop production costs and spiralling inflation. Unfortunately, crop prices have remained static. To investigate the impact of the increasing crop production costs, the 1976 and 1977 cost components were allowed to increase between 5% and 20%.

Regardless of the percentage increase within this range (5%-20%), 5000 acres and 7000 acres remained the constant optimal areas to irrigate under the expected utility and expected monetary value criteria, respectively. The maximum expected utilities and the maximum expected monetary values yielding the optimal acres decreased as the crop production costs increased.

The other input parameters whose variabilities could possibly impact the optimal strategy include the consumptive use, crop prices, crop yield, and the seasonal crop yield coefficient (GROWTH). Formal sensitivity analysis were not performed to investigate their impacts.

CHAPTER 9

SUMMARY AND CONCLUSIONS

9.1 SUMMARY

The irrigation systems designer and researcher have traditionally represented and quantified only the uncertainty inherently associated with the hydrologic phenomenon. Unfortunately, they have frequently failed to account for the spatial and time variabilities of the irrigation efficiency events in conjunction with the stochastic hydrologic input parameters. Others have completely ignored the risk response characteristics of farmers constantly faced with decision making under these uncertainties.

The obvious error of the certainty or deterministic irrigation efficiency assumptions that can seriously impact optimal irrigation systems design and management was the main objective of this study. A Bayesian decision theory optimization model was constructed and structured to investigate this impact. The developed model was tested using data collected from the Wood River Valley Irrigation District No. 45 located in central Idaho.

Using a 20 percent certainty irrigation efficiency yielded almost the same optimal acreages to irrigate during the same periods as considering probabilistic irrigation diversions in conjunction with probabilistic irrigation efficiency under a single crop system. However, higher maximum expected utilities and maximum expected monetary values were obtained in the deterministic than in the probabilistic model.

At a 40 percent certainty irrigation efficiency, the irrigation water supply regime for the district was predicted to be more than sufficient, at all times. This prediction does not conform with the actual water supply regime and the obtaining irrigated acreages in the district, implying that a 40 percent irrigation efficiency was too high for the existing irrigation system. For a probabilistic single crop system, greater optimal acreages, maximum expected utilities, and maximum expected monetary values were obtained in the period, P1 than in the period, P2. In the probabilistic multi-crop model, the optimal acreages were higher than under the probabilistic single crop setting during the first period, P1. The optimal areas did decline considerably during the period, P2, under the probabilistic multi-crop system to the point where negative expected monetary values were obtained.

Thus, in a probabilistic multi-crop setting, it would not be an economically sound management decision to irrigate wheat during this period, P2, unless research findings indicate that a polynomial type crop response is a certainty. The low seasonal crop yield coefficient suggests that the irrigation of wheat is not a critical factor influencing the total yield during this period. A good management strategy would then be to spend the available water supply on alfalfa or any high-value crops, and optimize water use. This implies a preferential irrigation strategy.

Both probabilistic single crop and multi-crop systems were sensitive to the crop response functions. A linear type crop response was a good approximation of an exponential type crop response function. The polynomial type function consistently yielded greater optimal strategy than the linear and the exponential types.

The crop models were also sensitive to the utility functions generated and used. A linear type utility function consistently generated greater optimal acreages and maximum expected benefits than the curvilinear function as the curvilinear function embodies risk response elements.

A family of optimal decision strategies would exist by separately deriving a utility function for each participating irrigator. Under a practical setting, the optimal management strategy for the entire system is frequently what the farm manager or the systems modeller seeks to achieve. Generating and using either of their utility functions may suffice.

The models were sensitive to the probability distribution function assumptions for irrigation efficiency. No significant difference existed between the normal and log-normal distribution postulates as both functions resulted in almost the same optimal strategy.

Updating and refining prior knowledge as a result of new data, using Bayesian methodology, yielded greater optimal areas and maximum expected benefits than both the normal and log-normal assumptions. This demonstrates the importance of new data. Most irrigation management adjustments are frequently made as new knowledge through research becomes available. The Laplace distribution yielded yet higher optimal areas and maximum expected benefits than were obtained under an improved knowledge situation (Bayesian Metholodogy).

Regardless of the amount assessed for irrigation water use, and the irrigation crop production cost, this methodology would consistently pick the same area as optimal, assuming that other input factors are held constant. The maximum expected benefits would frequently, however, be an inverse function of those cost components.

It can be concluded that the irrigation crop production cost factors and water assessment do not influence the optimum area to be seasonally committed to irrigation as much as the unreliable hydrologic, highly uncertain irrigation efficiency and variable seasonal crop yield factors.

Obviously, if the increase in the cost components resulted from the associated expenditure to upgrade management and improve water use, then the resulting more efficient system would naturally yield higher optimal areas to be seasonally irrigated. Thus, canal consolidation and lining efforts can positively influence optimal decision strategy.

9.2 CONCLUSIONS

The Bayesian decision theory optimization model was designed to be an irrigation management and planning tool rather than a design handbook. It mainly generates an optimal management strategy dictated by the risk and uncertainty inherently associated with assuming fixed and determinate values for the hydrologic and irrigation efficiency phenomena. Thus, it cannot prescribe means for either improving irrigation efficiency or adjusting the irrigation water supply regime existing in a district.

The irrigator is no more interested in improving irrigation efficiency than he is in protecting his surplus water right. Furthermore, his wasteful water use creates return flows that possibly maintain the water rights of his neighbors downstream. The irrigator understands that his water right is a legal certainty firmly controlled by a hydrologic uncertainty. When the supply is adequate, he must obtain his full right. If however, the water supply regime is inadequate, he would be interested in knowing what land to prepare for irrigation based on the available streamflow.

Thus, knowledge of the optimal policy to adopt that is controlled by the stochastic hydrologic and irrigation efficiency factors seems to be what the irrigator needs. Aware of a financial loss, he will still irrigate. To him, irrigation is not merely a business, but also a way of life which the threat of bankruptcy cannot disrupt. The results generated by this model could be important to such a farmer.

The optimization model has been demonstrated to be a functional tool for combining the limited existing data with new data, research findings and forecast as they become available, and so furnishes an updated and refined optimal strategy. This is particularly important as most improved management programs frequently result from research findings and new information. Thus, this model is also useful in already developed agriculture, where research and data generation form a strong component in irrigation technology.

Where data are scarce or limited, the model is flexible enough to accomodate entirely subjective and purely arbitrary substitutes where objective estimates should otherwise be made. In the developing nation, data scarcity is not uncommon. This model can still generate optimal decision strategies in the absence of complete data.

The model is simple, flexible, mission and man-oriented, and non-intensive in time and money. It could be particularly useful in developing nations with lagging technology and economy.

The model enhances communication between the farmer and the modeller. Uneducated irrigators in poor nations can still make useful contributions and be part of the decision-making process. The model considers directly the risk response functions of irrigators.

Outputs from Phase III optimization model utilizing various combinations of crop production cost, polynomial crop response, utility and seasonal crop yield functions, have compared rather well with the status quo present in the Wood River Valley Irrigation District. About 7000 acres are presently irrigated in the period, P1. This is cutback to about 4000 acres in the period, P2. Model output indicates that 6000 acres could be irrigated in the P1 period and 4000 acres during the second period, P2.

It can be concluded that the model has accomplished the study objectives.

CHAPTER X

PROBABLE ERRORS AND RECOMMENDATIONS

10.1 PROBABLE ERRORS

The Bayesian decision theory optimization model would definitely require some refinement to increase the reliability of the output and hence, expand its usefulness.

In the model development, some unrealistic assumptions were made that could possibly introduce serious errors. They are as follows:

1) The crop response functions. The three crop response functions used in the model are rather synthetic. They are not developed through research or field tests. The functions do not provide a penalty for over irrigation and leaching plant nutrients, or benefit for over-irrigation leaching excess salts. Under-irrigation is penalized but not strongly as it is well established that crop moisture stress beyond the permanent wilting point can lead to a total crop loss. The synthetic crop functions have not considered this moisture stress boundary.

Furthermore, it is unrealistic to use the same synthetic crop response functions for all the model crops. The uncertainty associated with this producure should be directly considered in the model.

2) Irrigation crop production cost function. The irrigation cost components applied in this model were those for the Twin Falls and Jerome Counties, assuming that they reflected the costs obtained in Blaine County. Brockway (1978) disapproved this assumption. In addition, only the costs for wheat and alfalfa were available, thus, limiting the crop combination actually considered.

3) The utility functions. The utility function used was the modeller's own function. A realistic model should incorporate the average utility for the farmers in the district or use the manager's own function.

4) Water assessment. A uniform water assessment was used for the entire district. It is established that water assessment for the district is a function of water rights.

5) Gravity irrigation system. The gravity unlined open canal system was studied. A combination of gravity and sprinkler systems should be considered if both systems obtain stochastic water supply from a common source; canal. This may involve incorporating "systems compatibility concepts" developed by Busch (1974).

6) Probabilistic independence of irrigation diversions and irrigation efficiency. This assumption should be investigated further to determine if it is realistic. It does appear that a conditional relationship exists between these stochastic events.

7) Discrete hydrologic and irrigation efficiency regimes. Both the hydrologic and irrigation efficiency events were assumed discrete. In reality, they are continuous functions that can take on any value within a regime. The probability that an event would occur from a continuous distribution is zero. That is, the probability that a variable will take on a certain value from a specified domain is zero.

Although a continuous-state model may seem more detailed and appropriate than a discrete-state consideration, any model that is more stable and accurate in generating optimal decision strategy should be employed.

8) Labor cost as a function of irrigation efficiency. Labor cost should realistically be a function of irrigation efficiency. Busch (1974) and Brockway (1978) stated that a high irrigation efficiency could understandably warrant high labor cost. As the irrigation efficiencies for the district's systems are generally low due to lack of maintenance, a fixed labor cost assumption may seem practically valid.

9) Consumptive use, CU. The consumptive use was assumed fixed during each irrigation period. This is really not true as consumptive use is a function of many factors including crops, time, climatological conditions and others. If fixed consumptive use values should be used, finer decision periods may be established.

10) Seasonal crop yield coefficients. The coefficients used were borrowed without modification. Their values are not supported by valid local research.

10.2 CURRENT RESEARCH NEEDS - RECOMMENDATIONS

The probable sources of errors definitely specify areas where current research effort is greatly needed. This is probably the most important achievement of this study; directing research focus on events that have not been adequately considered. The model is flexible enough to incorporate any new knowledge through research by making minor adjustments in the model configuration.

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APPENDICES

APPENDIX A

Irrigation Crop Production Costs

APPENDIX A

Table: 7A The Irrigation Crop Production Costs for the Twin Falls County

Crop: Alfalfa hay; Farm System: Large farm
2-year stand

Cost Components	Units	Price	Quantity	Value
Operating inputs:				
phosphate	lb	0.18	45.00	8.10
apply fertilizer	acre	2.50	0.50	1.25
insecticide	acre	6.00	0.50	3.00
custom stack	tons	3.75	5.00	18.75
ditch maintenance	acre	4.05	1.00	4.05
tractor fuel	acre			1.62
tractor repair	acre			0.73
tractor lube	acre			0.24
equipment fuel	acre			0.79
equipment lube	acre			0.12
equipment repair	acre			5.83
Total operating cost				$44.48
Capital cost:				
annual operating cost		0.08	21.22	1.70
tractor investment		0.08	25.84	2.07
equipment investment		0.08	103.29	8.26
irrigation system investment		0.08	1.88	0.15
Total interest charge				$12.18
Ownership cost: (depreciation, taxes, insurance)				
tractor				2.47
equipment				14.21
irrigation system				0.21
Total ownership cost				$16.89
Labor cost:				
machinery labor	hr	3.00	2.21	6.64
irrigation labor	hr	2.75	2.40	6.60
Total labor cost				$13.24
Overall production cost				$86.79

Table: 7B The Irrigation Crop Production Costs for the Twin Falls County

Crop: Alfalfa hay; Farm system: Small farm
2-year stand

Cost Components	Units	Price	Quantity	Value
Operating inputs:				
phosphate	lb	0.18	45.00	8.10
apply fertilizer	acre	2.50	0.50	1.25
insecticide	acre	6.00	0.50	3.00
custom swath	acre	5.00	3.00	15.00
custom stack	tons	3.75	5.00	18.75
ditch maintenance	acre	4.75	1.00	4.75
tractor fuel	acre			2.07
tractor repair	acre			1.03
tractor lube	acre			0.31
equipment repair	acre			1.99
Total operating cost				$56.25
Capital cost:				
annual operating capital		0.08	25.34	2.03
tractor investment		0.08	36.61	2.93
equipment investment		0.08	35.91	2.87
irrigation system investment		0.08	1.88	0.15
Total interest charge				$ 7.98
Ownership cost: (depreciation, taxes, insurance)				
tractor				3.62
equipment				4.92
irrigation system				0.21
Total ownership cost				$ 8.75
Labor cost:				
machinery labor	hr	3.00	1.46	4.37
irrigation labor	hr	2.75	2,40	6.60
Total labor cost				$10.97
Overall production cost				$83.95

Table: 7C The Irrigation Crop Production Costs for the Jerome County

Crop: Alfalfa hay; Farm system: Large farm

Cost Components	Units	Price	Quantity	Value
Operating inputs:				
phosphate	lb	0.18	23.00	4.14
apply fertilizer	acre	2.50	0.25	0.63
custom stack	tons	3.75	4.50	16.88
ditch maintenance	acre	4.05	1.00	4.05
tractor fuel	acre			1.99
tractor repair	acre			1.00
tractor lube	acre			0.30
equipment fuel	acre			0.79
equipment lube	acre			0.12
equipment repair	acre			6.00
Total operating cost				$35.89
Capital cost:				
annual operating capital		0.08	18.00	1.44
tractor investment		0.08	36.64	2.93
equipment investment		0.08	94.70	7.58
irrigation system investment		0.08	1.86	0.15
Total interest charge				$12.10
Ownership cost: (depreciation, taxes, insurance)				
tractor				3.61
equipment				13.03
irrigation system				0.21
Total ownership cost				$16.85
Labor cost:				
machinery labor	hr	3.00	2.21	6.64
irrigation labor	hr	2.75	2.40	6.60
Total labor cost				$13.24
Overall cost				$78.08

Table: 7D The Irrigation Crop Production Costs for the Jerome County

Crop: Alfalfa hay; Farm system: Small farm

Cost Components	Units	Price	Quantity	Value
Operating inputs:				
phosphate	lb	0.18	20.00	3.60
apply fertilizer	acre	2.50	0.20	0.50
custom stack	tons	3.75	4.50	16.88
ditch maintenance	acre	4.75	1.00	4.75
tractor fuel cost	acre			1.56
tractor repairs	acre			0.70
tractor lube	acre			0.23
equipment fuel	acre			0.79
equipment lube	acre			0.12
equipment repairs	acre			6.01
Total operating cost				$35.14
Capital cost:				
annual operating capital		0.08	17.00	1.42
tractor investment		0.08	18.91	1.51
equipment investment		0.08	94.53	7.56
irrigation system investment		0.08	1.88	0.15
Total interest charge				$10.65
Ownership cost: (depreciation, taxes, insurance)				
tractor				1.67
equipment				13.01
irrigation system				0.21
Total ownership cost				$14.89
Labor cost:				
machinery labor	hr	3.00	2.39	7.18
irrigation labor	hr	2.75	2.40	6.60
Total labor cost				$13.78
Overall cost				$74.46

Table 7E. Estimated Monthly Crop Growth Components Under Irrigated Conditions for SID, OPNBC, and NUID

Crop	March	April	May	June	July	Aug.	Sept.	Oct.
SID								
Field corn			1	2	3[b/]	4[a/]		
Alfalfa hay		1	1	2	3[a/]	2[b/]	1	
Pasture		1	1	2	3[a/]	2[b/]	1	
Mint			2	2	3[a/]	2[b/]	1	
Sugarbeets		1	1	2	2[a/]	2[b/]	2	
Potatoes			1	2	3[a/]	3[b/]	1	
Alfalfa seeds		2	2	2[b/]	2[a/]	1	1	
Corn silage			1	2	3[b/]	4[a/]		
Wheat		1	3[b/]	5[a/]	1			
Barley		1	1	3[b/]	4[a/]	1		
OPNBC								
Alfalfa hay		1	1	2	2[a/]	2[b/]	2	
Pasture		1	1	2	2[a/]	2[b/]	1	1
Sugarbeets		1	1	2	2[a/]	2[b]	2	
Potatoes			1	3	3[a/]	3[b/]		
Sweet corn			1	2	3[b/]	4[a/]		
Field corn			1	2	3[b/]	4[a/]		
Corn silage			1	2	3[b/]	4[a/]		
Alfalfa seeds		2	2	2[b/]	2[b/]	1		1
Onions	1	2	2	2[b/]	2[a/]	1		
Barley		1	1	3[b/]	4[a/]	1		
Wheat		1	3[b/]	5[a/]	1			
NUID								
Alfalfa hay		1	1	2	2[a/]	2[b/]	2	
Alfalfa seeds		2	2	2[b/]	2[a/]	1	1	
Wheat		1	3[b/]	5[a/]	1			
Pasture		1	1	2	2[a/]	2[b/]	2	
Mint			2	2	3[a/]	2[b/]	1	
Potatoes			1	3	3[a/]	3[b/]		
Barley		1	1	3[b/]	4[a/]	1		
Corn silage			1	2	3[b/]	4[a/]		

Source: Conklin, F.S., and W. E. Schmisseur (1976)

a/ month in which yield is most sensitive to water supply changes
b/ month in which yield is next most sensitive to water supply changes.
SID: Stanfield Irrigation District
OPNBC: Owyhee North Board Irrigation District
NUID: North Unit Irrigation District

Table: 7F a/Typical Balance Sheet for 3 Fiscal Years for the Wood River Valley Irrigation District No. 45

Category	Year	Year	Year
Receipts:			
cash on hand last fiscal year	2411.20	5879.71	81.94
current assessment Iwater right (water right)	6903.44	7221.45	8959.95
water master refund	150.00	150.00	150.00
insurance refund (workmans compensation)	26.00	-	76.00
maintenance loan	-	-	2200.00
Commodity credit (ASCS)	2563.46	1303.06	-
sale of equipment	-	700.00	-
Total receipts	$12054.07	$15254.22	$11467.89
Disbursements:			
directors per diem	300.00	300.00	-
machine hire	1275.25	7140.75	5176.21
ditch rider	2780.00	3162.50	3540.66
insurance (legal and workmen)	445.79	223.35	712.33
Social Security	221.05	212.64	242.22
employment tax			65.27
Secretary and Treasurer	300.00	300.00	297.00
security bonds	45.00	45.00	45.00
legal, stampls, advertising etc	53.94	57.20	113.69
attorney fee	-	-	161.00
materials	427.13	420.23	554.76
watermaster tax	105.16	202.60	239.15
Total disbursement			

a/ Source is C. W. Gardner, Wood River Valley Irrigation District No. 45

APPENDIX B

Computer Program Listings:
Single-crop and Multi-crop Systems

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C
C
C
C   OPTIMAL IRRIGATION MANAGEMENT STRATEGY UNDER HYDROLOGIC AND
C  IRRIGATION EFFICIENCY UNCERTAINTY REGIME
C
C
C
C
C   THE BAYESIAN DECISION THEORY OPTIMIZATION METHODOLOGY IS THE ADOPTED
C  TECHNIQUE
C
C
C   <************************************************
C  INVESTIGATION PHASE TWO
C         SINGLE CROP SYSTEM*******ALFALFA
C   <************************************************
C
C
C**************************************************************
C    FLOW(I) IS THE DISCRETE IRRIGATION DIVERSION ARRAY
C
C
C   PFLOW(I) IS THE DISCRETE PROBABILITY ARRAY OF THE OCCURRENCE OF
C  THE DISCRETE IRRIGATION DIVERSIONS
C
C
C  THE FREQUENCY ANALYSIS  IS THE PROBABILITY DENSITY FUNCTION
C   GENERATION TECHNIQUE FOR IRRIGATION DIVERSION
C
C
C  EFF(J) IS THE DISCRETE IRRIGATION EFFICIENCY ARRAY
C
C
C  PEFF(J) IS THE DISCRETE PROBABILITY ARRAY OF THE OCCURRENCE
C  OF THE DISCRETE IRRIGATION EFFICIENCIES
C
C
C  COEFF(I,J)  IS THE IRRIGATION WATER AVAILABILITY COEFFICIENT MATRIX
C
C
C  YADJ(I,J) IS THE CROP YIELD ADJUSTMENT COEFFICIENT MATRIX
C
C
C  DAC(I,J) IS THE CROP RESPONSE FUNCTION SHAPE FACTOR MATRIX
C
C
C  CREV(I,J) IS THE PER ACRE REVENUE MATRIX
C
C
C  TCREV(I,J) IS THE TOTAL REVENUE MATRIX FOR THE IRRIGATED AREA
C
CC   EMV(I,J) IS THE MATRIX OF THE EXPECTED MONETARY VALUE FOR EACH
C  ACTION--STATE COMBINATION
C  EU(I,J) IS THE MATRIX OF THE EXPECTED UTILITY FOR EACH ACTION--STATE
C  COMBINATION
C  UTILES (I,J) IS THE MATRIX OF THE UTILITIES FOR THE ACTION--STATE
C   COMBINATION
C
C
C
C********************************************************
      DIMENSION  FLOW(7),PFLOW(7),EFF(8),PEFF(8)
```

```
         DIMENSION  COEFF(7,8),EMV(7,8),CREV(7,8),TCREV(7,8),YADJ(7,8)
       DIMENSION DAC(7,8),EU(7,8),UTILES(7,8)
C
C
C
C  READ IN THE DISCRETE  IRRIGATION DIVERSIONS
         READ(5,5)  (FLOW(I),I=1,7)
 5       FORMAT(7F10.2)
C
C  READ IN THE DISCRETE PROBABILITIES OF OCCURRENCE OF THE DISCRETE
C   IRRIGATION DIVERSIONS
C
        READ(5,15)  (PFLOW(I),I=1,7)
  15     FORMAT(7F5.2)
C  READ IN THE DISCRETE IRRIGATION EFFICIENCIES
C
       READ(5,25) (EFF(J),J=1,8)
 25    FORMAT(8F6.2)
C  READ  IN THE DISCRETE PROBABILITIES OF OCCURRENCE OF THE DISCRETE
C   IRRIGATION EFFICIENCIES
C  THE IRRIGATION EFFICIENCY VARIATES ARE ASSUMED NORMALLY DISTRIBUTED
       READ(5,30) (PEFF(J),J=1,8)
 30        FORMAT(8F5.3)
C    READ IN MAXIMUM CROP YIELD
C   READ IN CROP WATER REQUIREMENT
C      READ IN WATER ASSESSMENT
C    READ IN CROP PRICE
C
C
       READ(5,35)  YMAX,CIR,WCOST,CRIZE
  35     FORMAT(4F6.2)
C  READ IN IRRIGATION COST COMPONENTS
C  OPINPT IS THE TOTAL OPERATING COST
C    CAPCT IS THE TOTAL CAPITAL COST
C    OWNCT IS THE TOTAL OWNERSHIP COST
C    XLABCT IS THE TOTAL LABOR COST
       READ(5,45)OPINPT,CAPCT,OWNCT,XLABCT
 45      FORMAT(4F6.2)
C  INPUT VARIABLE AREAS TO BE IRRIGATED
          DO  160  L=1000,10000,1000
C
         KAREA=L
C  INITIALIZE
C SUMA IS FOR MONEY IN DOLLARS
       SUMA=0.0
C  SUMEMV IS TOTAL EXPECTED MONETARY VALUE
        SUMEMV=0.0
C     SUMUT IS TOTAL EXPECTED UTILITIES
        SUMUT=0.0
C
C
C
C
C  WRITE AREA TO BE IRRIGATED
C WRITE  THE PERIOD CONSUMPTIVE USE
C  WRITE  WATER ASSESSMENT
        WRITE(6,153)KAREA,CIR,WCOST
 153   FORMAT(29X,'CROP',9X,'WATER',/9X,'CROP',4X,'AREA',5X,'REQU',
    1 8X,'COST'/16X,'(ACRES)',6X,'(FT)',8X,'($/AC-FT)',/7X,42('-')/7X,
    1  'ALFALFA',2X,I5,9X,F4.2,6X,F5.2///21X,'TOTAL CROP',4X,
    1 'TOTAL EXPECTED',4X,'TOTAL EXPECTED'/7X,'FLOW',3X,'EFFIC',
    1  3X,'REVENUE',5X,'MONETARY VALUE',6X,'UTILITIES'/7X,'(FT)',
    1  4X,'(%)',6X,'($)',13X,'($)',13X,'(UTILES)'/7X,60('-'))
```

```
C
C
        DO  150   I=1,7
         DO 152   J=1,8
C  ALL POSSIBLE COMBINATIONS OF IRRIGATION EFFICIENCY AND FLOW
C  COMPUTE CROP COEFFICIENT
       COEFF(I,J)=FLOW(I)*EFF(J)/(CIR*KAREA*100.)
C  LINEAR TYPE CROP RESPONSE FUNCTION ASSUMPTION
C
C
C  WHEN WATER IS OPTIMUM
         IF(COEFF(I,J).GE.1.0)  GO TO 40
C  LESS-THAN- OPTIMUM WATER SUPPLY REGIME
       YADJ(I,J)=YMAX*COEFF(I,J)
         GO TO 800
  40     COEFF(I,J)=1.0
         YADJ(I,J)=YMAX*COEFF(I,J)
C  COMPUTE PER ACRE CROP REVENUE
 800    CREV(I,J)=CRIZE*YADJ(I,J)-OPINPT-CAPCT-OWNCT-XLABCT
C  TOTAL REVENUE FOR TOTAL IRRIGATED AREA
       TCREV(I,J)=(CREV(I,J)*KAREA-WCOST*FLOW(I))/1000.0
C  SUM TOTAL REVENUE
       SUMA=SUMA+TCREV(I,J)
C  EMV CRITERION
        EMV(I,J)=TCREV(I,J)*PFLOW(I)*PEFF(J)
C  SUM  EMV
        SUMEMV=SUMEMV+EMV(I,J)
C       EU  CRITERION
        UTILES(I,J)=85.9+2.49E-02*TCREV(I,J)-1.59E-05*TCREV(I,J)**2
     1  +3.68E-09*TCREV(I,J)**3
       EU(I,J)=UTILES(I,J)*PFLOW(I)*PEFF(J)
        SUMUT=SUMUT+EU(I,J)
 152        CONTINUE
 150        CONTINUE
        WRITE(6,157) SUMA,SUMEMV  ,SUMUT
 157    FORMAT(7X,60('-')/12X,'TOTAL',4X,F11.2,3X,F15.2,3X,F11.2)
 160         CONTINUE
          STOP
         END
```

```
C
C
C
C    OPTIMAL IRRIGATION MANAGEMENT STRATEGY UNDER HYDROLOGIC AND
C   IRRIGATION EFFICIENCY UNCERTAINTY REGIME
C
C
C
C
C    THE BAYESIAN DECISION THEORY OPTIMIZATION METHODOLOGY IS THE ADOPTED
C   TECHNIQUE
C
C
C    <********************************************
C    INVESTIGATION PHASE THREE
C   MULTIPLE CROP SYSTEM*****WHEAT AND ALFALFA****
C    <********************************************
C
C
C************************************************************
C      FLOW(I) IS THE DISCRETE IRRIGATION DIVERSION ARRAY
C
C
C    PFLOW(I) IS THE DISCRETE PROBABILITY ARRAY OF THE OCCURRENCE OF
C   THE DISCRETE IRRIGATION DIVERSIONS
C
C
C   THE FREQUENCY ANALYSIS  IS THE PROBABILITY DENSITY FUNCTION
C    GENERATION TECHNIQUE FOR IRRIGATION DIVERSION
C
C
C   EFF(J) IS THE DISCRETE IRRIGATION EFFICIENCY ARRAY
C
C
C   PEFF(J) IS THE DISCRETE PROBABILITY ARRAY OF THE OCCURRENCE
C   OF THE DISCRETE IRRIGATION EFFICIENCIES
C
C
C   COEFF(I,J)  IS THE IRRIGATION WATER AVAILABILITY COEFFICIENT MATRIX
C
C
C   AYADJ(I,J) IS THE ALFALFA YIELD ADJUSTMENT COEFFICIENT MATRIX
C   WYADJ(I,J) IS THE WHEAT YIELD ADJUSTMENT COEFFICIENT MATRIX
C
C
C   DAC(I,J) IS THE CROP RESPONSE FUNCTION SHAPE FACTOR MATRIX
C
C
C   CREV(I,J) IS THE PER ACRE REVENUE MATRIX
C
C
C   TCREV(I,J) IS THE TOTAL REVENUE MATRIX FOR THE IRRIGATED AREA
C
CC   EMV(I,J) IS THE MATRIX OF THE EXPECTED MONETARY VALUE FOR EACH
C   ACTION--STATE COMBINATION
C   EU(I,J) IS THE MATRIX OF THE EXPECTED UTILITY FOR EACH ACTION--STATE
C   COMBINATION
C   UTILES (I,J) IS THE MATRIX OF THE UTILITIES FOR THE ACTION--STATE
C    COMBINATION
C
C
C
C******************************************************
```

```
       DIMENSION  FLOW(7),PFLOW(7),EFF(8),PEFF(8)
         DIMENSION  COEFF(7,8),EMV(7,8),CREV(7,8),TCREV(7,8),YADJ(7,8)
        DIMENSION  DAC(7,8),EU(7,3),UTILES(7,8),WYADJ(7,8),AYADJ(7,8)
C
C
C
C  READ IN THE DISCRETE  IRRIGATION DIVERSIONS
        READ(5,5)   (FLOW(I),I=1,7)
 5      FORMAT(7F10.2)
C
C  READ IN THE DISCRETE PROBABILITIES OF OCCURRENCE OF THE DISCRETE
C  IRRIGATION DIVERSIONS
C
        READ(5,15)  (PFLOW(I),I=1,7)
 15      FORMAT(7F5.2)
C  READ IN THE DISCRETE IRRIGATION EFFICIENCIES
C
       READ(5,25) (EFF(J),J=1,8)
 25    FORMAT(8F6.2)
C  READ IN THE DISCRETE PROBABILITIES OF OCCURRENCE OF THE DISCRETE
C  IRRIGATION EFFICIENCIES
C  THE IRRIGATION EFFICIENCY VARIATES ARE ASSUMED NORMALLY DISTRIBUTED
       READ(5,30) (PEFF(J),J=1,8)
 30          FORMAT(8F5.3)
C  READ IN MAXIMUM YIELD,YMAXAL,FOR ALFALFA
C   READ IN MAXIMUM YIELD,YMAXWH, FOR WHEAT
C  READ IN CROP WATER REQUIREMENT
C     READ IN WATER ASSESSMENT
C   READ IN CROP PRICE
C  READ IN WHEAT PRICE,WCRIZE, PER BUSHEL
C  READ IN ALFALFA PRICE,ACRIZE, PER TON
C
C
        READ (5,35) YMAXAL,YMAXWH,CIR,WCOST,ACRIZE,WCRIZE
 35     FORMAT(6F6.2)
C  READ IN IRRIGATION COST COMPONENTS
C  OPINPT IS THE TOTAL OPERATING COST
C   CAPCT IS THE TOTAL CAPITAL COST
C   OWNCT IS THE TOTAL OWNERSHIP COST
C   XLABCT IS THE TOTAL LABOR COST
C   GROWTH IS THE CROP YIELD  PER  PERIOD COEFFICIENT
       READ (5,45) OPINPT,CAPCT,OWNCT,XLABCT,GROWTH
 45     FORMAT(5F6.2)
C  INPUT VARIABLE AREAS TO BE IRRIGATED
          DO  160  L=1000,10000,1000
C
         KAREA=L
C  INITIALIZE
C SUMA IS FOR MONEY IN DOLLARS
       SUMA=0.0
C  SUMEMV IS TOTAL EXPECTED MONETARY VALUE
        SUMEMV=0.0
C     SUMUT IS TOTAL EXPECTED UTILITIES
        SUMUT=0.0
C
C
C
C
C  WRITE AREA TO BE IRRIGATED
C WRITE  THE PERIOD CONSUMPTIVE USE
C  WRITE  WATER ASSESSMENT
       WRITE(6,153)KAREA,CIR,WCOST
 153    FORMAT(29X,'CROP',9X,'WATER',/9X,'CROP',4X,'AREA',5X,'REQU',
```

```
     1 8X,'COST'/16X,'(ACRES)',6X,'(FT)',8X,'($/AC-FT)',/7X,42('-')/7X,
     1  '(ALFALFA)',2X,I5,9X,F4.2,6X,F5.2/'(WHEAT)'///21X,'TOTAL CROP',
     1  4X,
     1 'TOTAL EXPECTED',4X,'TOTAL EXPECTED'/7X,'FLOW',3X,'EFFIC',
     1  3X,'REVENUE',5X,'MONETARY VALUE',6X,'UTILITIES'/7X,'(FT)',
     1  4X,'(%)',6X,'($)',13X,'($)',13X,'(UTILES)'/7X,60('-'))
C
C
         DO  150   I=1,7
          DO 152   J=1,8
C   ALL POSSIBLE COMBINATIONS OF IRRIGATION EFFICIENCY AND FLOW
C   COMPUTE CROP COEFFICIENT
        COEFF(I,J)=FLOW(I)*EFF(J)/(CIR*KAREA*100.)
C   POLYNOMIAL TYPE CROP RESPONSE FUNCTION
C
C
C
C   WHEN WATER IS OPTIMUM
          IF(COEFF(I,J).GE.1.0)  GO TO 40
C   LESS-THAN- OPTIMUM WATER SUPPLY REGIME
        IF(COEFF(I,J).GT.0.25)  GO TO 115
        COEFF(I,J)=0.0
        AYADJ(I,J)=0.0
          WYADJ(I,J)=0.0
          GO TO 800
 115        DAC(I,J)=-1.03+4.8*COEFF (I,J)-2.8*COEFF(I,J) **2
         WYADJ(I,J)=YMAXWH*DAC(I,J)
       AYADJ(I,J)=YMAXAL*DAC(I,J)
         GO TO 800
  40       COEFF(I,J)=1.0
        WYADJ(I,J)=YMAXWH*COEFF(I,J)*GROWTH
          AYADJ(I,J)=YMAXAL*COEFF(I,J)
C   COMPUTE PER ACRE CROP REVENUE
 800       CREV(I,J)=ACRIZE*AYADJ(I,J)+WCRIZE*WYADJ(I,J)-OPINPT-CAPCT-OWNCT
     1   -XLABCT
C   TOTAL REVENUE FOR TOTAL IRRIGATED AREA
        TCREV(I,J)=(CREV(I,J)*KAREA-WCOST*FLOW(I))/1000.0
C   SUM TOTAL REVENUE
        SUMA=SUMA+TCREV(I,J)
C   EMV CRITERION
          EMV(I,J)=TCREV(I,J)*PFLOW(I)*PEFF(J)
C   SUM   EMV
          SUMEMV=SUMEMV+EMV(I,J)
C          EU  CRITERION
          UTILES(I,J)=85.9+2.49E-02*TCREV(I,J)-1.59E-05*TCREV(I,J)**2
     1   +3.68E-09*TCREV(I,J)**3
        EU(I,J)=UTILES(I,J)*PFLOW(I)*PEFF(J)
         SUMUT=SUMUT+EU(I,J)
 152          CONTINUE
 150          CONTINUE
         WRITE(6,157) SUMA,SUMEMV   ,SUMUT
 157     FORMAT(7X,60('-')/12X,'TOTAL',4X,F11.2,3X,F15.2,3X,F11.2)
 160           CONTINUE
           STOP
          END
```