TEXAS WATER DEVELOPMENT BOARD

REPORT 179

# ECONOMIC OPTIMIZATION AND SIMULATION TECHNIQUES FOR MANAGEMENT OF REGIONAL WATER RESOURCE SYSTEMS

A COMPLETION REPORT

Prepared By
Systems Engineering Division
Texas Water Development Board
and
Water Resources Engineers, Inc.

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February 1974

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# FOREWORD

In 1967 the Texas Water Development Board began a long-range program of applied research in water resource system simulation and optimization. The objective was to develop a set of generalized computer-oriented planning tools for use in detailed planning, design, and management of water resource systems such as the Texas Water System as proposed in the Texas Water Plan.

With the advice, encouragement, and financial assistance of the United States Department of the Interior, Office of Water Resources Research (OWRR), the guidance of an eminent research advisory panel, and the assistance of several consulting firms, the Texas Water Development Board has completed the final phase of a three-phase program. This volume summarizes the results of the third-phase effort, whose primary objective was to develop a practical method for evaluating and maximizing the primary economic benefits to an agricultural economy resulting from a large surface water resource system.

This report has been prepared for widespread dissemination for the purpose of informing water resource planners of the techniques developed during the research that may be of use in applying systems analysis procedures to the planning of water and related land resource systems.

Harry P. Burleigh

Harry P. Burleigh
Executive Director
Texas Water Development Board

# PREFACE

## Research Objective

The research described herein was conducted as the final phase of a three-phase effort to develop a computer-based methodology for use in the planning, design, and operation of a large, multibasin, multipurpose surface water resource system such as the proposed Texas Water System. The research was initiated to seek solutions to the problem of selecting which of a set of alternative water resource systems best achieves the objective of meeting water demands for all uses projected over a 50-year period under the following conditions: both water supply and demand are stochastic; and, at times during this 50-year period, certain projected demands for water cannot be met economically. The techniques developed during the three-phase research effort provide information for reaching planning decisions regarding the selection of the best alternative configuration of canals, reservoirs, and other elements of a surface water resource system to satisfy the stated problem objectives; when, during the implementation sequence, each of these elements should be constructed; the size of the elements (reservoirs, canals, etc.) of the system; the location, timing, and quantity of water which needs to be added from outside the system (imported) as a supplementary source; and how the water resource system should be operated to maximize the primary net benefits to agriculture and minimize economic losses during periods of water shortage.

The first phase of the research emphasized the development of deterministic simulation and optimization techniques for assisting the water resource planner to find the minimum-cost physical system and operational criteria for satisfying specified water demands using only one assumed hydrologic sequence. The second phase involved improvement of these techniques and the development of a methodology for quantifying the effect of variability (the stochastic component) in demand and supply on the configuration, implementation, and operation of the minimum-cost system.

The final phase of the research was initiated to develop a methodology for linking an economic analysis of the benefits to agriculture to the simulation-optimization procedures previously developed in order to maximize primary net benefits and minimize losses due to probable failures to meet specified demands. In addition, further enhancements were made to the techniques developed under the first two phases that increased their reliability and realism. Finally, a water quality model incorporating conservative water quality constituents was devised. The results of this final phase of the study are presented in this report.

## Description of the Report

This report discusses the procedures developed during the final phase of the project. Each of the newly developed procedures is discussed with the aid of an example problem based on the Texas Water System. A summary of this project, a discussion of the Texas water planning problem, a description of the relationship of this research to the previous two phases of work, and the conclusions reached from this phase are presented in Chapter I.

Chapter II presents the modifications to models developed in previous research to enhance their capabilities to simulate and optimize a prototype water resource system. This includes improvement of the multibasin simulation-optimization models and the technique used to fill in or generate stochastic hydrologic data.

Chapter III discusses the development of a rational approach for selecting operating rules for each reservoir in a multireservoir, multipurpose surface water system. An example of the application of this methodology to the Trans-Texas Division of the proposed Texas Water System is also presented in this discussion.

Chapter IV presents the main effort of this research project, the dynamic economic simulation of an irrigation water supply and its interactive application with the simulation-optimization model of a multibasin water resource system. This analytic technique permits irrigation water allocation to be adapted to the available and projected water supply. The technique maximizes net benefits while minimizing economic losses during periods of short supply. The application of this modeling system to the Texas High Plains agricultural area and the Trans-Texas Division of the proposed Texas Water System is described in detail as an example problem.

Chapter V describes a methodology which was developed to provide an analysis of the conservative mineral water quality (chloride, dissolved solids, etc.) in a previously selected multibasin surface water resource system. The technique, utilizing the results from an analysis with the simulation-optimization models and a selected hydrologic sequence, provides a spatial and temporal analysis of water quality in each element of the water resource system.

The models developed during this project are described in detail in separate program documentations which are a part of the overall Completion Report. These models and the volumes describing them are as follows:

| | |
|---|---|
| Allocation Model | – AL-III Program Description |
| Dynamic Economic Simulation Model | – DES Program Description |
| Multisite Data Fill-In and Sequence Generation Program | – MOSS-III Program Description |
| Multibasin Water Quality Simulation Model | – QNET-I Program Description |
| Multibasin Simulation and Optimization Model | – SIM-IV Program Description |
| River Basin Simulation Model | – SIMYLD-II Program Description |

## Organization

The Texas Water Development Board was responsible for overall research project management which was carried out under the general direction of Lewis B. Seward, Principal Engineer - Project Development. Mr. Seward, Mrs. Jean O. Williams, Program Controller, and Arden O. Weiss, former Director of the Systems Engineering Division, were instrumental in initiating the project and establishing and maintaining liaison with the Office of Water Resources Research.

Dr. Daniel E. Salcedo of the Systems Engineering Division, Dr. Herbert W. Grubb, of Texas Tech University and Texas Governor's Office, Dr. Wilbur L. Meier, Professor of Industrial Engineering at Texas A&M University, and Arden O. Weiss served as Co-Principal Investigators for the research project. Most of the material in this report was written by Dr. Salcedo and Dr. Lial F. Tischler, Director of the Systems Engineering Division. Dr. Salcedo was responsible for the development, testing, and documentation of the dynamic economic simulation model (DES) in addition to his efforts on this report. Carlos D. Puentes was responsible for the development, refinement, testing, and documentation of the multibasin simulation models SIMYLD-II and SIM-IV. James C. Wade refined, tested, and documented the MOSS-III hydrologic data fill-in and generation model. William A. White, Dr. T. Al Austin, and Dr. Tischler developed, tested, and documented the QNET-I system water quality model. Mr. White, Mr. Puentes, and Dr. Austin also reviewed and wrote various portions of the Completion Report.

Water Resources Engineers, Inc., under the general direction of its president, Dr. Gerald T. Orlob, developed and documented the reservoir operating rule selection methodology discussed in Chapter III. Dr. Ian P. King, under the direction of Donald E. Evenson, was responsible for developing and testing the five-step approach to operating rule development and wrote the major portion of the discussion of that technique reported herein.

Dr. Darwin Klingman and Richard Barr, of the University of Texas at Austin, developed and documented the new version of the out-of-kilter network optimization algorithm described in this report.

Norman R. Merryman of the Systems Engineering Division provided programming support for the dynamic economic simulation models, and Dr. Rex P. Kennedy of Texas Tech University provided agricultural data for its use. Arthur R. Simkins of the Economics, Water Requirements, and Uses Division supplied agricultural and cost data for the dynamic economic simulation models. Leonard W. Carter and Glenn D. Merschbrock of the Systems Engineering Division provided technician support throughout the research project. Mrs. Diana Giddings of the Systems Engineering Division was responsible for assembling and editing the Completion Report, including the program documentation volumes.

Assistance in all phases of the research and of report preparation was received from the Consulting Panel: Dean Dean F. Peterson, Chairman; Harvey O. Banks; Leo R. Beard; Dr. Ven Te Chow; and Dr. Herbert W. Grubb. Throughout the project the Consulting Panel reviewed progress and provided valuable guidance to the research staff.

## Acknowledgments

The output of this research, as documented in this Completion Report, would not have been possible without the enthusiastic support and involvement of many individuals and the agencies they represent.

First, the research team wishes to acknowledge the support given the project by the Texas Water Development Board, its members individually, and Harry P. Burleigh, Executive Director.

The advice and encouragement given by Dr. H. G. Hershey, former Director, Dr. Edward G. Altouney, former Research Scientist, and Leonard R. Brown, Research Scientist, all of the Office of Water Resources Research, are greatly appreciated.

Special thanks are due to Dr. Paul A. Jensen, University of Texas at Austin, for continued advisory assistance throughout the three-phase project and for originally suggesting the use of the out-of-kilter algorithm for solving the systems simulation problems.

To these individuals, and others who have encouraged the program from its inception to its present state, the researchers express their sincere appreciation.

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# ECONOMIC OPTIMIZATION AND SIMULATION TECHNIQUES FOR MANAGEMENT OF REGIONAL WATER RESOURCE SYSTEMS

## A COMPLETION REPORT

## I. SUMMARY AND CONCLUSIONS

### Objectives of the Research

As the remaining available uncommitted supplies of water and land resources diminish and demands for them increase, the objectives of water resources planning broaden, the physical facilities required become more complex, and the limitations under which they must be implemented become more stringent. There exists an urgent need to develop techniques which can enhance the capability of the planners to make an intelligent and comprehensive evaluation of alternatives. Because costs of construction, operation, and maintenance of water resources facilities are likely to be large, a means must be found for analyzing alternative solutions to water problems. Because of the tremendous complexity of the systems that must be considered in a large-scale water resources planning problem, planners have been turning to sophisticated mathematical techniques applied on digital computers of increasing speed and accuracy. The basis for these techniques is the representation of the physical system by a set of mathematical relationships which can be solved quickly and efficiently by high-speed digital computers. Care must be taken to insure that this mathematical analog is representative of those aspects of the planning problem which can be quantified and at the same time is compatible with methods for including factors in the analysis which are not immediately quantifiable. This research builds on the experience gained in the previous two research efforts, which is documented in Reports 118 and 131 (Texas Water Development Board, 1970, 1971), to provide comprehensive techniques for assisting planners to improve the scope and depth of water resources planning work.

The objectives of this research project are to:

1. Develop methods for measuring the economic impact that may be expected to result from shortages of water occurring in large water resource systems. The scope of this objective comprises the development of an analytical model or models to evaluate the economic effects of intensity, duration, frequency, and timing of shortages and to determine the optimum level of water delivery that will result in the most effective economic and physical use of available water supply.
2. Modify existing optimization and simulation procedures as may be needed to provide minimum-cost optimization capabilities for any desired level of development.
3. Modify existing techniques for generating stochastic streamflows and demands to provide probabilities of given levels of performance.
4. Integrate the above methodologies into a self-contained water resources planning package capable of determining the optimal trade-off between increased returns from higher uses in water-rich seasons and losses from subtarget performances during low-flow periods.
5. Use a portion of the proposed Texas Water System as a real-world problem to test the optimization and simulation procedures developed during this research.
6. Provide for further development of the research and usage capabilities of the Texas Water Development Board's in-house staff.

A set of models named Dynamic Economic Simulation (DES) was developed to satisfy objective number one. These models are capable of simulating the demand for and use of irrigation water. DES also traces the effects that different climatologic and irrigation supply sequences have on the physical yield of a multifarm, multicrop area and the corresponding economic impacts. With this tool, the effects of hydrologic sequences of varying intensity, duration, and frequency and the timing of shortages can be analyzed.

The second objective was achieved in previous research but was further enhanced during the course of this study by the addition of a refined version of the algorithm to all of the network optimization models.

Regarding objective (3), much was accomplished in enhancing the techniques for filling in and generating stochastic hydrologic data as described in the MOSS-III program description volume which is a part of this report. However, no work was done on evaluating probabilities of given fixed levels of performance because the DES system was made to be adaptive to changing decisions rather than static with a stochastic component. This is not to indicate that efforts to estimate the probabilities of system performance levels should not be the subject of additional research. The fourth and fifth objectives were achieved by integrating the DES system with the enhanced versions of the previously existing multibasin simulation and optimization models. Data from the Trans-Texas Division of the Texas Water Plan (Texas Water Development Board, 1968) were used to illustrate how DES might be used in water resources planning. Additionally, a technique was developed to trace the transport of conservative water quality constituents through an interbasin transfer system.

The sixth objective was realized, as in the previous two years, by working with a consulting panel of prominent experts in the water resources field. As an outgrowth of this research effort, the Systems Engineering Division staff has grown in size and sophistication and efforts have expanded into the modeling of water quality, ground water, ecological, and economic systems.

## The Texas Water Plan - A Planning Problem

In 1964, recognizing the need for a more orderly and longer range analysis of the State's water problems, water needs, and solutions to these problems, Governor John Connally requested that a comprehensive State Water Plan be prepared by the then Texas Water Commission. The planning function of this agency was soon after realigned into the present Texas Water Development Board. The newly created Board prepared and released the Texas Water Plan in 1968. The Texas Water Plan is a guide for the orderly development, conservation, and management of the State's water and related land resources to meet the needs of the people of Texas to the year 2020.

More specifically, the objective of the Plan is to provide the water supplies, and other benefits derived from water development, that are necessary to meet water needs throughout Texas as the State grows and its economy expands.

Other major concepts (Boswell, 1968) used in formulating the Plan include:

- The Plan must be flexible if it is to meet changing conditions.
- The Plan is based on the premise of no interference with vested rights, including the protection of in-basin water rights.
- Implementation of the Plan will be a coordinated and cooperative effort of the Federal government, the State, and political subdivisions of the State.
- In general, water basin sources, sites, and facilities are to be developed on a multipurpose basis.
- Adequate inflows of fresh water will be provided for the bays and estuaries.
- Maximum assistance of the Federal government and its agencies will be sought, but water users will be expected to pay most of the costs of development of the water resources.

To accomplish its objectives, the Plan contains a detailed inventory of the water resources of Texas, projected demands for water, and some proposed methods for satisfying these demands.

Estimates of future water demands were made using conventional methods for projections of economic development, population growth, and of the future of irrigated agriculture. Water requirements for municipal and industrial use and for irrigation were based on average unit values. The Board estimated the available water resources, basing the firm yields of reservoirs on modified runoff records with each reservoir considered separately.*

After estimating the demands for water and the available water resources within the State, the Board found that the demands exceeded the available in-state supply at the end of the planning horizon (2020). The sources of in-state water that the Board evaluated included water from surface streams, water from underground formations, treated and untreated wastewaters, and brackish or saline water. The Board concluded that in order to meet the total projected demands water must be imported from out-of-state sources. For planning purposes, it was assumed that surplus waters from the Mississippi River could be diverted below Louisiana's last point of diversion. This left the problem of identifying, within the State's financial, legal, political, and other constraints, the best physical works required to accomplish the objectives of the Texas Water Plan.

The general nature and locations of the physical facilities required have been determined with reasonable certainty. However, the sizes, sequencing, and the staging of the many physical elements have only been determined approximately. The major facilities of the Plan include:

- the Texas Water System,
- interstate system (import and export),

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* Available ground-water resources were estimated on current withdrawal rates and aquifer characteristics.

- projects to meet local requirements, and
- facilities for purposes other than water supply.

To provide an example problem for use in the research described in this and previous reports, the Board selected the Trans-Texas Division of the Texas Water System; it is shown in red in Figure 1. The Texas Water Plan (1968) and Texas Water Development Board Reports 118 (1970) and 131 (1971) fully describe this system.

The Trans-Texas Division is comprised, as illustrated schematically in Figure 2, of two major components: a major demand area lying primarily in the High Plains of West Texas and New Mexico and an in-state supply area comprised of parts of four river basins in East Texas. Although the greatest quantity of the High Plains demands is for agricultural use, there are significant municipal and industrial demands included in the service area. The system may also receive water from an out-of-state source to meet incremental demands in excess of in-state supplies. A distinguishing feature of the overall system is its size; more than 700 miles separate the major demand centers from the out-of-state sources of import water. In addition to the hundreds of miles of interconnected canals and natural waterways, there would be 22 reservoirs in the Trans-Texas Division. Pumping facilities would be required to lift flows through about 3,500 feet of elevation from near sea level to the High Plains of West Texas.

The System has the following unique characteristics which further complicate the planning problem:

- the potentially developable terminal storage sites in the demand area are scarce,
- the only major sources of water supply in the major demand area (West Texas) are ground waters and these are rapidly being depleted,
- the potential developable reservoir sites in the in-state supply basins have a maximum cumulative capacity to supply the maximum system demand for only a single year of operation,
- the surface water supplies of in-state basins are highly variable, both seasonally and annually,
- the proposed sources of imported water can be drawn on for only a fraction of the year, at the most about 50 percent of the time, and
- the maximum demands on the system may be expected to occur during months when imported water will not be available and runoff is low, hence peak demands must be met primarily from stored in-state and import supplies.

Legal, political, and physical considerations all suggest a planning period of about 50 years. Over such a span of time it is anticipated that demands will rise steadily, even dramatically in some areas.

## Future Planning Problems

Planning for the Texas Water System will have to continue and be completed in much greater detail before the design phase can be initiated. The system is so complex, will serve so many diverse and widespread demands from so many different sources, will involve so many physical facilities, and be so costly, that detailed, thorough planning is essential. Such planning requires the use of advanced techniques that are available or that can be developed. The result will be not only lowered costs but also increased benefits by an expanded service.

Among the many problems the Board now faces in its planning activities, the following are of paramount significance:

- The estimates of future water demands for the several uses must be refined. Better estimates of the extent and pattern of future economic development, of population growth and distribution, and of unit water demands are essential. Detailed studies of the hydrology, hydraulics, biology, and ecology, and of the uses to be made of the bays and estuaries, are required to quantify the amounts and regimen of the necessary fresh water inflows. Since the demands for irrigation in the High Plains of West Texas, which will be the largest single demand on the system, are dependent, to a significant degree, on rainfall, they must be analyzed on a probabilistic basis. In addition, increasing cost of water will result in more efficient use resulting, in turn, in lower future demands—this aspect, too, needs in-depth study.
- A more thorough analysis of the water resources available—surface, underground, and return flows—is needed. Surface water resources must be subjected to probability analysis to obtain better estimates of the quantities and variations in quantities of surface water that will be available. This must be done not only on an individual river

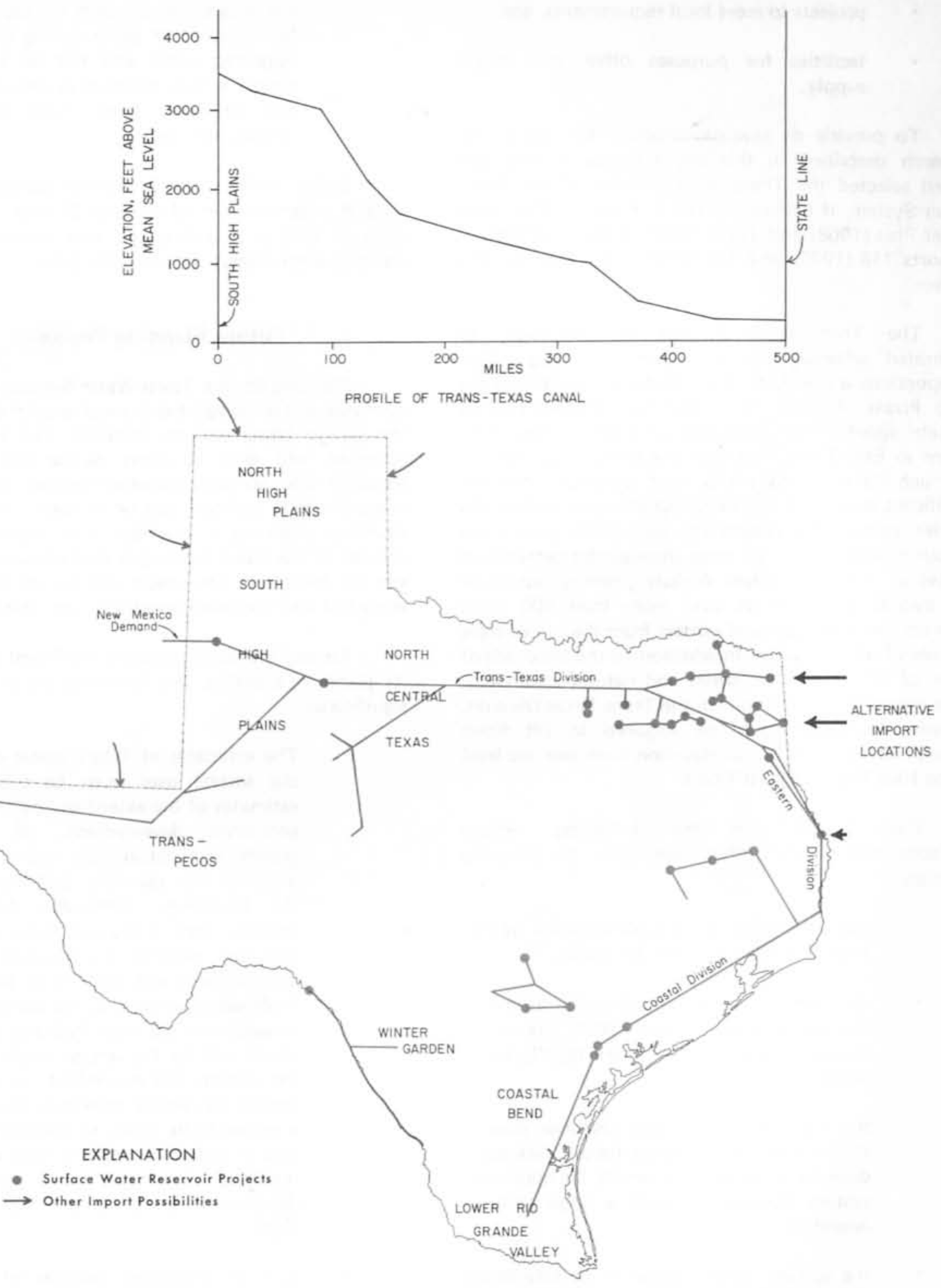


Figure 1

Schematic Diagram of the Texas Water System

(Includes major conveyance facilities and related reservoirs)

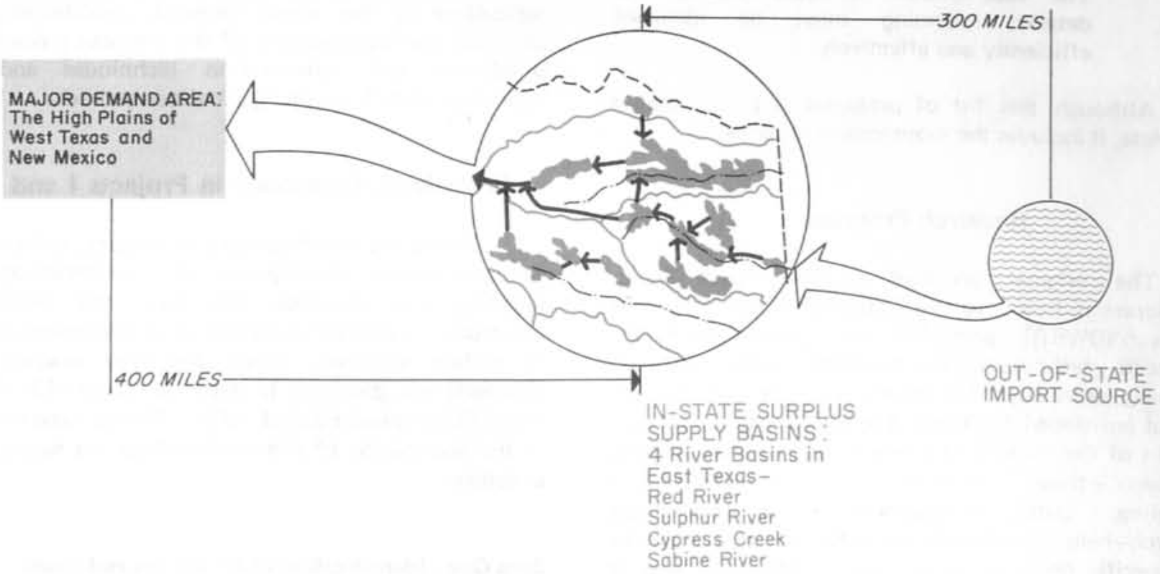


**Figure 2. Major Supply and Demand Areas for the Trans-Texas Division of the Texas Water System**

basin basis, but also on combinations of river basins with different hydrologic characteristics.

- The impact of recent developments in wastewater treatment technology and discharge water quality criteria on water availability must be analyzed. Increased waste treatment requirements and costs will likely have a considerable effect on wastewater reuse and thus on return flow availability. Wastewater reuse must also be considered as an alternative to transfers of surface and ground waters.

- Desalting of saline and/or brackish waters, both surface and ground, must also be considered as alternative water supplies where such saline water supplies are available. Technological advances may make desalting and wastewater reuse competitive with interbasin transfers of water in some areas.

- The quality of the water delivered by any water resource system must be suitable for each intended use. The quality of water required for domestic uses is not necessarily suitable for the organisms in an aquatic ecosystem. For example, salt content has a direct effect on the suitability of water for irrigation of certain crops. It is important for the planner to consider the economic impact of precluding certain crops from an irrigated area because of water quality considerations. Similarly, the hardness of water supplied for municipal and industrial uses has a bearing on treatment and consumer costs. The list of water quality considerations is long, and the planner must, if possible and if the information is available, evaluate all potential impacts.

- The environmental effects of any water resources plan and each of its elements must be carefully analyzed. Both beneficial and detrimental effects on ecosystems must be identified, and, if possible, quantified.

- The market and non-market benefits and costs of water resources projects must be evaluated. In particular, the secondary and tertiary effects of water supply projects on regional and national economies should be considered.

- Conjunctive use of underground water resources, particularly the Ogallala Formation underlying the High Plains of West Texas, with the surface water to be supplied must be investigated.

- The configuration, sizing, sequencing, and staging of the physical facilities required to supply water from the resources available must take into account the probabilities of occurrence of both resources and demands.

- Operational criteria for water resources projects must be developed on a systematic basis to maximize yield and minimize costs.

- Institutional arrangements for the operation of completed water resource systems must also be made.

The vast amount of data required for detailed planning must be managed efficiently and effectively.

Although this list of problems is by no means complete, it includes the more important ones.

## Research Program

The original proposal of the Texas Water Development Board to the Office of Water Resources Research (OWRR) presented the general need for advanced techniques to facilitate water resource planning, especially of unusually complex systems such as that envisioned for Texas. The Board determined that certain of the techniques characteristic of the "systems approach"—those identified with mathematical modeling, data management, and operations research—held considerable potential for adaptation to the specific needs of water resource planners. Also, it was asserted that the prospect for future beneficial application would be greatly enhanced if the necessary research and development could be carried out in the context of a real planning problem. The Board proposed, and OWRR concurred, that the Trans-Texas Division of the Texas Water System be identified as the real case in point and that the research programs be structured accordingly.

Consequently, the Board initiated a research effort consisting of three projects, each building on the previous years' results. The three projects, each providing a more complete analysis of the planning problem, can be summarized as follows:

### Project I

Development of deterministic simulation and optimization techniques for assisting the planner to find the minimum-cost physical system and operational criteria for satisfying deterministic water demands with a single set of specified hydrologic conditions.

### Project II

Development of a set of practical procedures and techniques for quantifying the effect that stochastic variability has on the structure, implementation, and operation of the minimum-expected-cost physical system referred to above, and improvement of the simulation and optimization modeling techniques.

### Project III

Development of practical methods which can be used to evaluate and maximize the net benefits to agriculture (considering both supply and demand) realized from a large water resource system where agriculture is the major demand. Additionally, to continue the improvement of the previously developed simulation and optimization techniques and the hydrologic data fill-in and generation methods.

## Procedures Developed in Projects I and II

During the first two years of research, efforts were centered around development of a methodology for selecting the sequence, the size, the timing of construction, and the operation of an interconnected set of surface reservoirs, canals, and river reaches. This approach was discussed in detail in Report 131 (Texas Water Development Board, 1971). The six steps involved in the application of this methodology are summarized as follows:

### Step One - Identification of Objectives and Goals

Step One consists of identifying the goals to be met and the purposes to be served. This is perhaps the most difficult job of the planning process, but is the most important, and must be done before an optimal implementation plan can be found. It was suggested that planners using the strategy should (1) specify an objective or goal that serves the purposes defined as important in their orders of priority, (2) strive to find the resulting implementation plan to meet the goal, and (3) then decide, based upon the trade-offs present and risks involved, if the selected development plan or a modified version of it representing a lower or higher risk plan should be implemented. Meeting demands at minimum expected cost, with minimum shortages, is one of the possible objectives that could be specified.

### Step Two - Analysis and Development of Data Base

Step Two consists of developing a comprehensive data base for use in Steps Three through Six. This step requires two major types of data preparation activities. The first activity is that of developing, for use in the simulation and optimization models, a stochastic hydrologic data base comprised of

- refined runoff or reservoir inflow data,
- gross evaporation or climatic index data,
- net lake-surface evaporation data developed from rainfall data and gross evaporation data,
- irrigation water requirements developed by a consumptive use model, and
- municipal and industrial water requirements.

The second activity comprises the development of parameters which describe the system and the problem being studied, such as

- cost-capacity-elevation-area relationships for each reservoir and canal being considered in the analysis,

- the discount rate, repayment period, reservoir financing lag time, and pump-canal financing lag time used to calculate present value costs of capital investment and operation and maintenance costs, and

- data describing the physical and other characteristics of the system being analyzed.

To enhance the results of this step, trend analysis programs, fill-in programs, stochastic data generation programs, and flow refinement and projection programs were used to help preserve the appropriate cross and serial correlations within each of the data sets, and thus develop a sound comprehensive data base at various levels of basin development for all subsequent steps in the planning and design process.

One of the unique characteristics of this methodology is the treatment of the stochastic element in both the runoff and the demands for water. Therefore, in addition to using a refined historical filled-in data set, a large number of stochastic data sets of rainfall, runoff, evaporation, and unit demands for water can also be used.

The technique used in Project II to estimate irrigation demands involved the use of a soil moisture and consumptive use model which used rainfall data, evaporation data, soil and cropping data, and irrigation efficiency to generate monthly unit-acre irrigation demands. The total regional demand for irrigation water was obtained by using assumed cropping patterns and total irrigated acreage within the demand region.

For the demand points within the Texas High Plains this procedure results in a demand sequence that varies about a trend line as shown in Figure 3. This particular demand sequence represents the time stream of projected irrigation demands based on projected cropping patterns and historical precipitation and evaporation records. It corresponds to the historical period used to generate the yearly inflows to the example problem reservoirs, also shown in Figure 3. It must be recognized that these inflow and demand sequences represent only one set of a very large number of supply and demand sequences which are equally likely to occur in the future. The trend line is a direct function of both the number of acres that are irrigated with surface water and the average annual rainfall contributions, whereas the jagged line represents the expected annual water usage based upon rainfall and evapotranspiration stochastic variability. The trend line shown in Figure 3 is comprised of the moving average stochastic irrigation demand plus a non-stochastic, increasing municipal and industrial demand quantity.

The water supply.also has a stochastic component. The variability of that component may be as great or greater than the demand variability, depending on the characteristics of the problem. An indication of the relative variability of the demand and supply is given in Figure 3 for the 36-year demand-buildup period. Figure 3 illustrates that, for most of the time during the demand-buildup period, import water is required to meet, on the average, demands for water to irrigate a specified fixed number of acres.

### Step Three - Plan Development Based on Historical Data

Step Three consists of an initial analysis of the river basins and portions of river basins comprising the multibasin planning problem. The purposes of this analysis are to

- determine how best to control the available runoff,

- compute the amount of water that the system can be expected to yield,

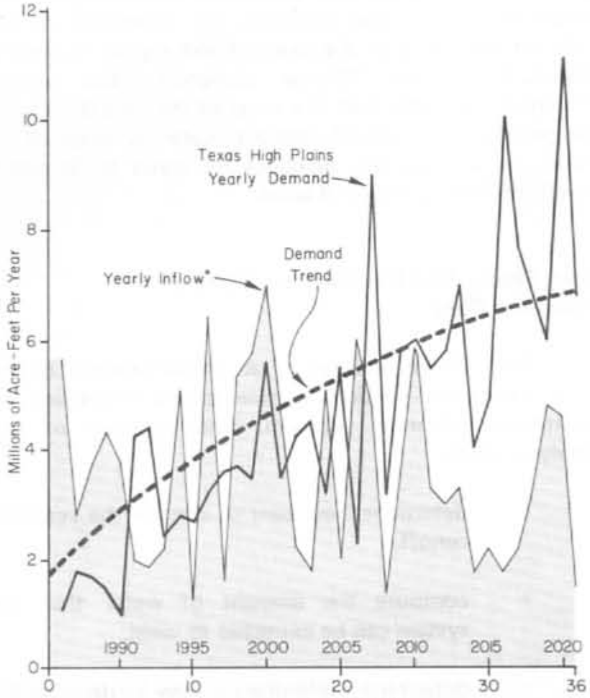
- determine preliminarily how to develop the best set of storage and transfer facilities to move available supplies to use areas, and

- determine preliminarily the magnitude of the demands that can be met with the available supply.

From a water supply viewpoint, various locations and sizes of possible reservoirs were investigated in an attempt to find the storage arrangement that controls the runoff in each watershed at minimum unit storage cost (dollars per acre-foot of storage), yet makes sure that the major storage reservoirs, if possible, are near the major in-basin demand points.

The aid in this process SIMYLD-I, a river basin simulation and optimization model, was developed. SIMYLD-I computes the firm yield for any specified network of reservoirs and interconnecting river reaches and pump-canals with given maximum capacities and seasonal low-flow release constraints. The firm yields computed can and should be based upon numerous practicable assumptions about (1) seasonal distribution of the imposed demands and (2) spatial location of the demand within or external to the basin storage configuration. These computations were performed under various projected levels of watershed development (e.g., 1990, 2000, 2010, and 2020 conditions) using, as input, the refined historical and projected data base developed in Step Two.

A set of reservoirs in the supply and demand basins, having specific locations and sizes, is a partial result of this step. Figure 4 shows the system configuration developed in this step and pertinent demand and supply relationships.



*The sum of unregulated inflows to the reservoirs comprising the example problem; not including import

Figure 3. Stochastic Variability of Inflow and Demand

### Step Four - Plan Improvement Based on Historical Data

Step Four used several simulation models, primarily SIM-III and AL-II, to help find "good" fixed plans at various demand levels (e.g., the 1990, 2000, 2010, and 2020 levels) using the refined historical data base projected to various future times on the demand buildup curve. This analysis was based on evaluating system performance of selected alternative sets of canals, reservoirs, and operation criteria over a specified economic life. A penalty cost was used to account for the economic impact of water shortages. This penalty cost, multiplied by the shortages (in acre-feet), resulted in the total penalty for failure to meet demands.

Based upon a series of initial simulations of the entire network, with each canal's maximum capacity set at a relatively high value, the models computed

- the amount of usage that each of the canals would get during the 36-year simulation period,
- the absolute maximum flow in each of the canals, and
- the ratios of maximum to mean flow in each of the canals.

Based upon these observations and the change in the economic response of the system (i.e., the total cost change) resulting from the iterative use of SIM-III and AL-II, certain canals of very low usage were eliminated from further consideration. The maximum-capacity constraints of each of the canals left in the network were successively reduced, from simulation to simulation, to levels that approached a minimum-cost solution. Here, the total cost response was the sum of (1) the construction costs multiplied by a present worth factor equal to unity, and (2) the sum of annual operation costs over a 100-year period.

Upon preliminary sizing of the ultimate ditch portion of the canal facility, the analysis was directed towards finding an optimal system (location, size, and operation criteria) for specified points on the demand buildup curve starting with the earliest point first.

### Step Five - Plan Optimization Based on Historical and Stochastic Data

Step Five is designed to analyze and improve the "good" but sub-optimal plans derived in Step Four, using both the historical and selected stochastic sequences of hydrologic and corresponding demand data generated in Step Two. The SIM-III model was used for the detailed analyses performed in Step Five. Step Five was also designed to

- quantify the impact that location of drought within the demand buildup period, in addition to magnitude, duration, and frequency of drought occurrence, has on selecting the optimal implementation plan,
- quantify changes in the "good" plans derived in Step Four which are required to secure more cost-effective (in terms of minimizing total costs) performance, and
- find the single implementation plan (the minimum-cost plan) which performs better against the historical and synthetic buildup in demand and project supply sequences than any other plan.

### Step Six - Variability and Sensitivity Analysis

Step Six is the last step in the multibasin planning strategy discussed and consists of an extensive variability and sensitivity analysis. The purpose of this analysis is to subject the minimum-expected-cost plan found in Step Five to conditions other than the specified "best

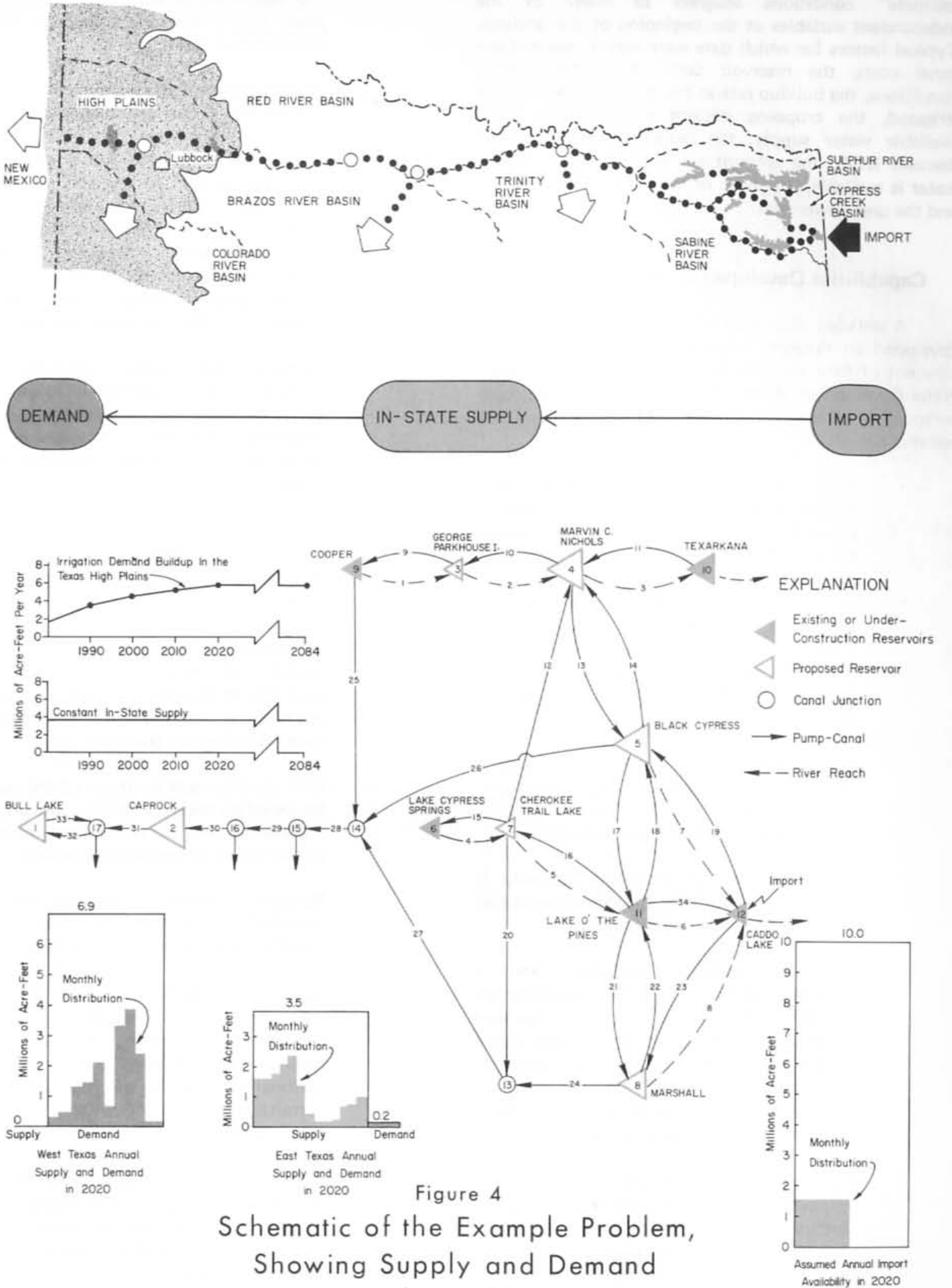


Figure 4

Schematic of the Example Problem, Showing Supply and Demand Relationships estimate" conditions assigned to many of the independent variables at the beginning of the analysis. Typical factors for which data were varied included the canal costs, the reservoir costs, the initial storage conditions, the buildup rate in the number of acres to be irrigated, the cropping pattern variables, the mean available water supply, the municipal and industrial demand levels, the amount and time at which import water is available, the mean of the evaporation variable, and the unit power cost.

## Capabilities Developed in Projects I and II

A detailed discussion of the modeling capabilities developed in Projects I and II and the assumptions inherent in their use is presented in Report 131 (Texas Water Development Board, 1971). To provide the proper perspective, these capabilities and assumptions are restated below:

- Only mass balance quantitative surface water is modeled; that is, no water quality parameters or conjunctive use of ground water is included in the modeling capability.

- Monthly time increments are used in simulating the system; thus, operations of canals and reservoirs for routing flood waves are not considered. Therefore, the total travel time within the system must be less than one month.

- The models are capable of analyzing a network configuration of reservoirs, pump-canals, and river reaches interconnected in any possible manner.

- The resolution of modeling accuracy is currently set at 1,000 acre-feet as controlled by the resolution of the input data.

- Both a "perfect knowledge" and a "forecast" version of modeling capability are available. By definition, the "perfect knowledge" capability looks one year ahead at the supply and demand data prior to solving the problem for that year, whereas the "forecast" capability does not look ahead at the hydrology prior to solution.

- Two options are available upon which to optimize monthly internodal water transfers. One uses only unit pumping costs; the other uses the unit pumping costs plus prorated capital costs to calculate total unit cost to pump.

- Lower constraints can be set on demands to reflect, at each node, how much of a specified demand must be met regardless of the magnitude of shortages incurred. If the lower bounds are set too high, an infeasible solution may result.

- Construction staging increments of 10 years will be used in the general analysis.

- All demands for and inputs of water are specified except for import waters. The maximum available import water will be prespecified. In other words, runoff, evaporation, system losses, and demands for water are forced upon the system, but import water is drawn upon only when needed up to the maximum available.

- Demands for water, reservoir inflow quantities, and evaporation rates can be varied on a month-by-month basis to permit accounting for demand buildup, runoff depletion, and stochastic variability in all of these quantities.

- The methodology is capable of handling a problem with a 100-year economic life and a 36-year simulation period (e.g., 1985 to 2020).

- A minimum-cost objective consisting of capital and operating costs and a penalty cost due to shortages is used. If these costs are realistic, then maximum net benefits are realized under this criterion.

- Unit penalty costs for incurred shortages can be varied by node by season, whereas pricing preferences for reservoir storage alternatives can be varied by reservoir by season.

- Because an economic objective criterion is specified, a specified economic value for meeting demands versus the economic value of storing water is required. Therefore, demands for water will be met only if the value for meeting demands is greater than the penalty for meeting them. The value of having water in specific reservoirs on a seasonal basis can be specified, but it is not permitted to interact with the value of meeting demands. By design, Project III permits the value of storing water to interact with the value of meeting demands on a monthly basis. Spills out of the system are, by definition, the least desirable alternative use of water. Therefore, spills will occur only as a last resort.

- The physical system can be represented by a set of interconnected nodes and links. Links correspond to river reaches and lengths of canals, while nodes represent reservoirs and link junctions.

- All water demands and inputs can occur only at nodes.

- Canal evaporation can be estimated for long reaches and withdrawn at nodes.

- Canal seepage losses can be estimated for long reaches and withdrawn at nodes.

- Import can occur at any storage or non-storage node in the system during any limited part of the year up to the maximum monthly availability that was specified.

- The maximum amount of import water available can be changed at any yearly interval with a maximum of four different levels being permissible. However, a constant seasonal distribution of the available import water is assumed.

- Those reservoirs that are capable of accepting import water can be specified as a means to control the amount of water imported and its locations of interim storage.

- Both reservoirs and canals can be added to the network of active facilities at any given year in the simulation period. A maximum of four sizes (stages) can be specified during this period. This can be increased with little trouble.

- Both minimum and maximum flow and storage capacities can be specified for canals and reservoirs, respectively.

- Canal costs are divided into two components—that component which cannot be staged (e.g., ditch, right-of-way, and related costs) and that component which can be staged (e.g., pump, motor, power, and housing costs). For staged components, the simulation model is capable of imposing a penalty cost for capital expansion, expressed as a percentage of the total expansion cost.

- The preference to pump upstream from a reservoir, instead of releasing water downstream when the reservoir is overflowing, can be specified on a link-by-link basis.

- The transmission capacity of the ditch portion of the canal facility for the last year of the simulation period can be larger than the actual pump capacity of the canal facility to allow for future expansion.

- Spills out of the system (system losses) can be controlled to occur at only those reservoirs specified as spill nodes.

Some of the limitations of the approach used in the first two years of research include the following:

1. A minimum-cost objective function was specified. In determining the worth of the implementation of a project, it is necessary to have measures of benefit with which to compare the costs incurred. A search for the minimum-cost means of meeting a specified demand is justified only in cases where the demand is precisely known and is assured to more than justify the cost incurred in meeting it. The penalty-cost concept for forcing the delivery of water has a basic assumption that the costs for not meeting demands are linear over all ranges, which is invalid for most demands. These penalty costs are at best very difficult to define.

2. It was assumed that the demand levels were specified both regionally and sequentially. This assumption stems from the fact that with the previous approach the irrigation demands were computed using a simple soil moisture accounting model that calls for irrigation water to fill up the soil reservoir whenever it drops below 50 percent of capacity. The input to this demand model is a sequence of rainfall and evapotranspiration values which are used to calculate the fluctuation in the soil moisture reservoir.

   The number of acres served, as well as the cropping pattern, are specified according to projections made without knowledge of water availability. This characteristic of the modeling technique is unrealistic because it does not take into account the fact that farmers will adapt their strategies rationally to make the most favorable use of variable amounts of water available under varying climatic conditions. Also, the maximum number of acres to be served, i.e., the total project service area, may also be limited by the costs of the distribution system; in other words, it may not be justified to provide for service to all of the project area that could be served only infrequently.

3. The modeling techniques, when used without a "look-ahead" capability to predict future hydrologic events, tended to empty reservoirs to satisfy demands during the current month unless constraints were put on the end-of-month storage levels. During Projects I and II, fixed levels of storage at the end of each month were assigned to some reservoirs while other reservoirs were allowed to float between maximum capacity and minimum capacity. The fixed levels, which were selected solely through

experience with the models, were crucial to providing more than just a local optimum and were the key to the predicted system operation. In order to minimize this "trial and error" procedure and to provide more realistic simulation of reservoir levels (obviously an empty reservoir at the end of each month is unacceptable), new methods for determining operating rules were required.

4. The effects of water quality were not considered. A plan that is optimal strictly from the standpoint of water quantity may be undesirable when water quality is considered.

The objectives of Project III, as previously presented, were intended to eliminate, or at least minimize, the effects of these limitations on the analysis of a large water resource system. The following chapters of this report discuss, in detail, how these objectives were satisfied and how the methodology developed during the three projects can be used to provide the planner with the information he needs to formulate and evaluate a water resource system with the capability to satisfy the objectives for which it was designed.

## Conclusions of Project III

The conclusions resulting from the final phase of a three-year project research effort are summarized as follows:

- The six-step planning procedure previously developed and reported in Report 131, of the Texas Water Development Board (1971) is a valid approach to obtain the optimal configuration for a multibasin water resource system. However, a more detailed analysis of system operation and response to stochastic hydrology and irrigation demands than was provided by Projects I and II is required to determine the best system operating rules and final hydraulic element sizes if net benefits are to be maximized. The models developed in this research were designed to provide this more detailed analytical capability to the planning framework established in Projects I and II.

- A methodology which can be used to simulate the adaptive nature of competing farmers' irrigation decisions which are based upon the changing status of their crops during a growing season subject to highly variable precipitation, evaporation, and surface water supply is computationally practical. The methodology presented relies upon the interactive use of an irrigation demand model and a simulation-optimization model of a multibasin water resource system. The irrigation demand model is adaptive to changing conditions of water availability and is based upon two external optimization analyses. A dynamic programming model develops maximum returns and decisions for scheduling the irrigation of one crop on one soil, while a linear programming model is used to select optimal cropping patterns for various amounts of soil moisture and surface water availability using the return information from the dynamic programming model. These analyses serve as input for a dynamic simulation of competing farmers' rational decisions based upon changes in water availability and crop status. This technique permits the maximization of net benefits to an irrigated agriculture region for every growing season in an area subject to highly variable water availability.

- A rational methodology can be used for determination of reservoir operating rules for complex systems of reservoirs and canals. The technique presented utilizes the "look-ahead" capability of the previously developed allocation model to arrive at a set of monthly target storages for each reservoir in a system. However, the optimization routine used in the allocation model causes it to be incapable of using monthly storage levels to calculate evaporation losses and pump costs, which somewhat restricts the value of the method. Additional experience with systems other than the example problem is needed to enhance the reliability of the technique. It is felt that this rational approach to operating rule development is a useful technique for establishing "real-world" rules for use in a simulation model of a multibasin water resource system.

- Monthly operating rules for each reservoir in a multibasin water resource system add considerably to the realism of system simulation-optimization models such as have been developed and used in this research project. By specifying monthly target storage levels for each reservoir in a system and assigning priorities for meeting demands, the models come considerably closer to the actual allocation of water in a prototype surface water system.

- A methodology has been developed which will perform a postaudit evaluation of the water quality (for conservative constituents, e.g., chloride) in a multibasin water resource system. The technique developed uses the results from simulation-optimization model studies and information on the water quality of all water sources to predict the distribution of water quality in a water resource system. This analysis provides the water resource planner with additional important information for evaluating alternative plans for meeting demands for water.

Improvements in model capabilities and basic data result in considerable improvement in the analytical results. As expected, the closer the simulation approaches the operation and configuration of an actual water resource system, the greater is the utility and reliability of the information obtained. Potential users of these techniques are cautioned that the most refined model is only as reliable as the basic data used in the modeling analysis.

# II. ENHANCEMENTS TO PREVIOUSLY EXISTING MODELS

A significant portion of the effort in this year's project was directed toward improvements of models developed in the first two years of research. It has been the experience at the Texas Water Development Board that the task of working with systems models is never complete. During the course of an extended study such as this, the original assumptions used in developing the analytical techniques become too restrictive, and modifications are made to reduce the limitations of the systems analysis techniques. Considerable improvements in the original models were realized in the second year research project, as documented in Report 131 (Texas Water Development Board, 1971).

During the third-phase Project, additional improvements were made to the multibasin simulation models SIMYLD-I, AL-II, and SIM-III. These models simulate the operation of a large-scale water resource system with many reservoirs and demand points interconnected by canals and natural river reaches. Additionally, the techniques previously used for developing reservoir operating rules for a multibasin system were basically trial and error. Experience with the system was required before a truly optimal (or realistic) system operation could be developed. Finally, the technique described in Report 131 for hydrologic data fill-in and generation was not fully capable of preserving the important statistical characteristics of the historical records. This technique was modified and subsequently produced better results, although still with some error.

## Multibasin Systems Simulation and Optimization Techniques

SIMYLD-I, SIM-III, and AL-II are detailed simulation programs with imbedded flow optimization criteria. They were the refined results of the first two years of research and are the basic tools of the planning methodology which has been developed. The basic concepts behind these models were presented in Report 118 (Texas Water Development Board, 1970), and the enhancements added during Project II were discussed in Report 131 (Texas Water Development Board, 1971) and its attendant program documentation volumes. Although the SIMYLD-I, SIM-III, and AL-II models were flexible and useful tools after the previous enhancements, certain additional limitations could be identified which were corrected in this project. The foremost of these was the lack of a means for keeping the contents of reservoirs at selected "desired" levels between maximum and minimum capacities. The previous simulation models had no constraints on reservoir storage other than the upper and lower limits, which permitted the levels within each reservoir to fluctuate widely from month to month during a typical simulation period. Since in a real system it is almost mandatory to maintain (or at least attempt to maintain) certain reservoir storage levels in order to meet the demands of recreation, fish and wildlife, power production, and flood control, the simulation models were modified to permit the use of reservoir operating rules to specify "desired" monthly storage levels. A method for developing these rules is presented in Chapter III.

In addition to the changes required to permit the use of monthly operating rules in the models, an improved version of the imbedded optimization algorithm was added to each model. This algorithm results in a significant reduction in analysis time for a given network flow problem and is discussed in detail in the program documentation volume of each model using it. Finally, some modifications were necessary in the SIM-IV model to permit it to operate in conjunction with the economics-demand simulation model. This procedure is discussed in detail in Chapter IV.

The following brief discussions of the SIMYLD-II and SIM-IV models are amplified in the detailed program documentations. The modified version of the AL-II model is discussed in some detail in Chapter III.

### SIMYLD-II

The purpose of this model is to provide the water resource planner with a tool for analyzing water storage and water transfer within a multireservoir or multibasin system. The program is designed to simulate both small-scale systems, such as two or three reservoirs within one river basin, and large-scale systems such as the proposed Texas Water System.

SIMYLD-II has two primary uses. The first is to simulate the operation of a system subject to a specified sequence of demands and hydrology. In this mode the model simulates the movement of water in a system of reservoirs, rivers, and conduits on a monthly basis while attempting to meet a set of specified demands in a given order of priority. If a shortage(s) occurs (i.e., not all demands can be met for a particular time period) during the operation, they are spatially located at the lowest priority demand location(s).

The second use of SIMYLD-II is to determine the firm yield of a reservoir within a water resource system. Firm yield is defined as the maximum demand at a reservoir that can be met with no shortages. This capability is useful for determining, for example, the water available for export at the lowest priority demand location in a basin system while meeting all demands of a higher priority. By operating the storage facilities as an interconnected system, the firm yield of a given reservoir can be increased considerably over that realized by operating each reservoir independently. An iterative procedure is used to adjust the demands at the designated reservoir in order to converge on its firm yield at a given storage capacity.

The model is also designed to provide the user with flexibility in selecting operating rules for each reservoir. The operating rules are formulated as the percentage of the reservoir capacity (either total or conservation) that is desired to be held in storage at the end of each month. In addition, a priority ranking, used to determine the allocation of water between meeting demands and maintaining storage, is assigned to each storage reservoir. The operating rules provide flexibility by allowing the user to vary the monthly desired reservoir storage levels during the year and to vary the priority of allocation of water between satisfying demands and maintaining storage in the reservoirs.

SIMYLD-II can analyze either static or dynamic system operation, in that both constant and time-variable demands can be analyzed. This provides the user with the flexibility of analyzing the operation of a system subject to increasing or decreasing trends in water requirements. In addition, the operation of the system under the expected ultimate demands can be analyzed for any selected hydrologic sequence.

An example problem illustrating the use of SIMYLD-II is presented in the detailed program documentation volume.

### SIM-IV

The SIM-IV model, primarily because of the bulk and intricacy of both the input and output, is presently restricted to the configuration of the Trans-Texas Division of the Texas Water System. However, the techniques described in the detailed program documentation report can be easily implemented on a wide range of planning problems in many different geographic locations. Moreover, because each individual problem has its own unique characteristics, a completely generalized model would not provide the flexibility that each problem requires.

Modifications to the SIM-III model which resulted in the SIM-IV model include the addition of the capability of assigning intermediate "desired" storage levels as in SIMYLD-II. This change also permits the utilization of the operating rules for the various reservoirs in a water resource system developed by the technique described in the next chapter.

The SIM-III model also required certain changes to permit it to operate conjunctively with the dynamic economic simulation model of an irrigation system, which is discussed in detail in Chapter IV of this report. These changes involve, principally, providing the capability to estimate, from a current month's storage in selected "key" reservoirs, the supply which should be available through the remaining portion of the annual growing season. This forecasting feature is based upon the total water stored in the system at the start of the growing season and is updated as each successive month in the annual hydrologic sequence is realized. This technique is applied by initially performing a detailed hydrologic analysis of the major water supply area. In particular, the seasonal distribution of the runoff in the supply area is important in this analysis. Estimates of potentially available water supply at the beginning of and throughout a growing season can be made, with a specified statistical reliability, by using a probability analysis of these seasonal runoff characteristics. The probability analysis of the historical record permits the estimation, based on the current and preceding month's streamflows and reservoir storages, of the water available for the remainder of the months in the growing (irrigation) period. The analysis also provides statistical information on the likelihood of these predictions being realized. For example, if the January and February streamflows in East Texas and the reservoir storages are known, the January through August water availability can be estimated with a certain reliability, say, ±50 percent. In May, the January through August water availability can be predicted within ±10 percent, etc. This information is supplied to the irrigation system simulation model in the form of predicted available supplies.

In the example problem this strategy works well, since most of the runoff in the East Texas supply area occurs during the first four months of the year, while the crop planting in the irrigation demand area usually begins in the fifth month. Obviously, the specific probelm used in this research permits this technique to work more effectively than it might in regions where seasonal hydrologic patterns are not so well defined. However, the technique used should still prove valuable inasmuch as it is representative of the actual operation of a water supply system where water is allocated to each user at the beginning of the growing season based upon the available storage, and alterations in this allocation are made as time progresses and the hydrologic conditions change. Additionally, the SIM-IV model also uses the refined version of the optimization algorithm which results in more cost-efficient analyses of a water resource system.

## Hydrologic Data Fill-In and Generation

The monthly streamflow simulation computer program (HEC-4) developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers has been adapted by the Texas Water Development Board for use in reconstituting missing hydrologic data and generating synthetic sequences for studies of the Texas Water Plan. This program, referred to as MOSS, as used in Project II (Texas Water Development Board, 1971) had several limitations that seriously affected the utility of the program and the reliability of the results. These were:

- No provision was made for filling in data for more than ten sites in a region, whereas there may be a need to fill in dozens or even hundreds of sites in large-scale water resource studies.

- Occasional extreme and unreasonable monthly quantities of streamflow and precipitation were generated in test runs, which indicated that there was a fundamental error in the reconstitution (and generation) process.

- Average filled-in or generated flows for long sequences tended to be larger than average observed flows, which cast additional doubt on the model's validity.

- In generating repeated sequences of synthetic streamflows, it was the experience of the Hydrologic Engineering Center and the Texas Water Development Board that extreme observed droughts in some regions could not be equalled in severity. This suggested that the multiple linear regression Markov chain model used in MOSS does not adequately represent nature.

- The model contained an undesirable arbitrary truncation provision designed to reduce the likelihood of generating the extremely large values previously mentioned. This was objectionable because it is an artificial constraint.

- The model would not accept negative quantities, and it is necessary to consider some variables having these, such as negative net evaporation (net precipitation).

A number of modifications, as detailed below, were made to eliminate or minimize the effects of these limitations in the MOSS model.

### Multipass Provision

Because of the size of the correlation matrix ($24N^2$) and the fact that it increases with the square of the number of sites, N, it is not reasonable to preserve cross-correlations between all possible pairs of sites when their number increases beyond eight to ten. This is due to core size limitations in electronic digital computers and, more universally and permanently, to possible instability of the correlation matrix. In order to reconstruct or generate data for a large number of interrelated sites, it is therefore necessary to perform the desired operation for eight to ten sites at a time in a series of passes. As each new site group is operated upon, selected sites from previous passes are included in such a manner that the essential intercorrelation among sites is preserved. The provision devised makes use of magnetic scratch tapes and is discussed in the detailed program documentation volume which is part of this report.

This multipass provision makes it possible to reconstruct and generate data for any number of sites while preserving essentially all important intercorrelations among sites, provided that sites are grouped with care and operated upon in the proper sequence. Considerable judgment is required in selecting the order in which sites are entered into a multipass generation. As a general guide, long-record sites in as many regions as possible should be included in the first pass in order to establish a framework that indicates cyclic fluctuations in all regions. In subsequent passes, each new site should be accompanied by one or two of these long-record sites from earlier passes that best correlate with the new site. Shortest-record sites should be held until last. The basic judgment is that if the high intercorrelations are preserved, the lower intercorrelations will also be preserved to a major extent.

### Prevention of Unreasonable Generated Values

Occasional extreme values were generated in past applications of this model. Some of the extreme values have been so large that it could be concluded that they could not reasonably be expected to occur in nature. In order to determine the sources of the extremely large values, a detailed analysis of the program was performed. The values for the transformed flows at various operational stages in the program were of particular importance. From this information it was determined that the problem was due to the inadequate representation of the sample data distribution by the Pearson Type III function used in the model. The first three moments (mean, variance, and skew functions) of the sample data are, in fact, inadequate for tranforming the sample data to a standardized normal distribution.

Since the sample data did not exactly fit the Pearson Type III distribution, some constraints or adjustments must be made if the multiple linear regression techniques of the MOSS model are to be used. Such constraints are highly undesirable if they are not based on the physical process being simulated. Therefore, emphasis was placed on adjustments designed to guard against irregularities resulting from the approximations of the sample data. The approximate Pearson Type III transformation is the step where the basic problems existed.

The initial transformation of the logarithms of the sample quantities from what is an approximately Pearson Type III distribution to the standardized normal distribution is an initial step of the program. When the sample data distribution is radically different from the Pearson Type III distribution, such as when a large number of observations are zero, extreme values of mean and variance will not be preserved and the resulting distribution will not be normal. In order to preserve the mean and variance (of the transformed values) in the transformation process, the sum of the squares of positive values after the transformation is made equal to half the sum of the squares of the values (streamflow) before the transformation. The sum of the squares of the negative values after transformation is also made equal to half, so that the total variance is preserved. This is done by dividing all transformed values by the appropriate ratio, which can be different for negative and positive values. Ratios used are stored for use in retransforming these observed (historical) sample values so that exact historical streamflow can be printed out later.

Even with this adjustment to guard against bad transformations, occasional unreasonable values can occur. To minimize this possibility, skew coefficients are constrained within the range between minus 0.7 and plus 0.7. This is not the type of constraint that is highly objectionable because it is part of the selection of the transform function, which is an arbitrary selection based upon experience and observation. It should be noted that, unless a far more elaborate fitting process (than the use of three moments) is used, there is no transformation function possible that will guarantee that the transformed values will conform to the Gaussian normal distribution. As long as the multiple linear regression technique is being used, it is essential that variables be transformed to Gaussian normal in order to assure linearity and to assure that the variance is preserved when combining the correlated and random components. The entire theory of linear regression is based on the assumption that all variables are normally distributed.

It should be further noted that the objection to bad transformations is in connection with the use of multiple linear regression as a generation model, wherein extreme values for one month or site will result in extreme generated values for another month or site where the transformation function (moments) is different. Thus, while the originally transformed extreme values will transform back to reasonable values, the newly generated values will not necessarily transform to reasonable streamflow quantities for the different month or site.

After streamflows are reconstituted or new flow sequences are generated in terms of standardized variates, their transform to Pearson Type III variates is also controlled to assure that the variance of the untransformed value is preserved. This is accomplished by multiplying all transformed values by an appropriate constant, which is the same for positive and negative values. The function to which the values are being transformed is not necessarily symmetrical about zero, as in the case of the standardized normal distribution, and consequently, the symmetry of the transform should not be controlled. This operation is performed for reconstituted and generated streamflows.

### Preservation of Average Flow

Analysis has shown that the generation of unreasonable streamflow values is accompanied by the generation of other erroneous values that are not as noticeably in error. Such errors can be larger in the positive direction than in the negative direction, because distributions of streamflows are generally positively skewed. These errors account for the tendency of long-term mean generated flows to be too high when compared to historical sequences. Tests made, since the adjustments described in the preceding section were incorporated into the program, indicate that this may explain the tendency of the long-term means to be high. Accordingly, no additional program modifications were required for this specific problem.

### Generation of Extreme Droughts

The inability of MOSS to generate hydrologic sequences containing extended drought periods as severe and as long in duration as some actually recorded in history is attributed to the likelihood that the persistence of low flows has different characteristics than the persistence of high flows, whereas MOSS applies random components uniformly for low and high flows.

To account for variation of the random component with the size of the streamflow, the random components of observed streamflows are computed using the regression equations derived from them. The average absolute value of the error (random component) for deviations above the mean and the average absolute value of the error for deviations below the mean are computed. Similarly, the average value for the positive deviations and the average absolute value of the negative deviations are computed. A linear function is then established that relates the error magnitude to the size of flow computed from the regression equation. This provides for random components that can be larger for large generated values and smaller for small generated values, or the reverse of this if indicated by observed data relationships, but the standard error of the regresssion equation is applied as in the traditional process if a value exactly equal to the mean is generated.

### Elimination of Truncation Provision

In the process of reconstructing data or generating new sequences, a provision had been included in the original Hydrologic Engineering Center model to moderate the generation of large flows on streams where flows vary greatly (as in arid and semiarid regions). Where standard deviations of logarithms exceeded 0.3 for any site or month, extrapolation of the frequency curve beyond two standard deviations above the mean was continued at a slope of 0.3 rather than at the full slope corresponding to the computed standard deviation.

This provision has been eliminated from the process and no apparent adverse consequences have resulted, probably as a result of the other changes that have been made.

### Generation of Negative Quantities

The model as developed at the Hydrologic Engineering Center had a provision for truncating negative generated flows at zero. This provision has proved to work very well for streamflows in that the number of generated zero flows usually corresponds reasonably with the number observed in the actual record.

In order to permit the use of negative numbers for some variable (such as net evaporation), it was necessary to change the indicator of missing data from -1 to -9999 at several places in the program. This will permit operating on variables having negative values as large as -9998. There is a provision in the program to check whether negative values exist in observed data. If they do, generated values are not truncated at zero. Thus, the program can be used directly to fill in or generate evaporation and precipitation records.

### Additional Program Changes

Several other improvements have been made in Program MOSS. Notable among these are a selective print-out option and a smoothing of the statistics used in generating new flow sequences. The print option provides several levels of print-out describing the fill-in and/or generation results.

The original smoothing routines for the computed statistics (Beard, 1965) have been eliminated from MOSS because of the possibility of creating problems in the reconstruction of hydrologic data. It was felt that such smoothing could not be used with the other corrective measures applied to the program and discussed herein without serious likelihood of problems. However, for synthetic sequence generation some smoothing of the frequency statistics can be applied. Therefore, a smoothing routine is now included for use in the generation process only.

### Effects of Model Enhancements

The changes described above permit reasonably reliable use of the MOSS program for reconstructing and generating new sequences of hydrologic data of several types using any number of interrelated sites. Of particular significance are the multipass provision and the elaborate controls placed on the Pearson Type III transform function. Tests have demonstrated that generation and reconstruction problems previously encountered are no longer in evidence. However, it is still theoretically possible to generate unreasonable quantities if extremely erratic sample data should occur. This is particularly important if historical records are short (less than 15 years). It is thus necessary to scrutinize the model results carefully in each new application.

# III. DEVELOPMENT OF OPERATING RULES

The effectiveness of an optimum development plan for a multibasin system of reservoirs and canals is eventually dependent upon the ability to operate the system in an optimal fashion. Therefore, a major portion of the effort in this research went toward developing a procedure for obtaining "operating rules that specify releases and pumping rates for a system of reservoirs and canals, the sizes of which have already been specified by previous analyses."

The procedure presented here is based on monthly operating periods, and thus, it can only be considered as a procedure to describe the general operation of the system. This limitation is in keeping with the assumptions originally stated for the analysis of the planning problem. In order to achieve the objective of efficiency, the optimum operating rules that are sought are ones which minimize pumping and shortage penalty costs for the system as a whole. The overall objective of the water supply system is to meet the required supply of water at a minimum expense. The capital cost of the system is fixed once the system elements have been selected as described in the previous report on Project II (Texas Water Development Board, 1971). Thus, costs incurred from system operations are for operation and maintenance (principally power for pumping in the example problem) and the penalty costs assessed for failure to meet the specified demands. Thus, in developing refined operating rules it is necessary to minimize pumping and penalty costs for the entire water resource system to insure optimal operation.

SIM-III is a simulation-optimization model which allocates water optimally a month at a time without any knowledge of future hydrology or demands. In this sense SIM-III is similar to the operation of a real water system. As a result of its lack of knowledge of future events, SIM-III will tend to empty reservoirs to satisfy demands in the current month unless constraints are put on the end-of-month reservoir storage levels. The initial versions of SIM-III used fixed levels of storage at the end of each month for most reservoirs, while other reservoirs were permitted to vary between maximum and minimum capacity. These fixed storage levels were determined through experience gained using the models on the system. These storage levels were crucial to providing a solution which was optimal for the entire system rather than for any individual reservoir and, also, were the key to the predicted operations of the system.

Several alternative methods for developing improved operating rules present themselves. These are:

1. Develop fixed minimum storage levels for each reservoir for each month,
2. Develop desired (target) monthly releases from reservoirs based upon current storage plus monthly inflow and demands, and
3. Develop desired (target) reservoir storage levels for each month and associate a benefit with achieving these levels.

Method 1 is essentially a single reservoir rule procedure in which minimum storage levels are set by consideration of a low-flow year or sequence of low-flow years and the expected demands from the reservoir. This procedure, if applied to a multireservoir system, ignores the possibility of conjunctive use of reservoirs that may raise the system yield considerably. To set minimum reservoir storage levels based upon consideration of a conjunctive use pattern requires the use of a simulation-optimization model such as SIM-III to evaluate their effectiveness. Fixed storage levels which must be maintained could make the optimization problem highly constrained or perhaps infeasible in some cases. If the constraints are relaxed so that minimum levels apply only to a few reservoirs, excessive transfers between reservoirs can occur, which may result in high pumping costs. The main problem with this approach is that it may require numerous trials to get a good solution.

Method 2 is the common single reservoir operating rule and is shown graphically in Figure 5. The monthly reservoir release is dependent upon the sum of end-of-month storage and current month inflow into the reservoir. The monthly reservoir release target is that amount of water which must be released to meet downstream demands and any low-flow requirements for the current month. If the reservoir is empty and current month inflow is less than the demands, shortages will be taken (lower portion of curve, Figure 5). When the reservoir storage plus the current month's inflow exceeds the maximum reservoir capacity, excess water above demands must be released (the reservoir spills). In between these extremes monthly release requirements can be met exactly.

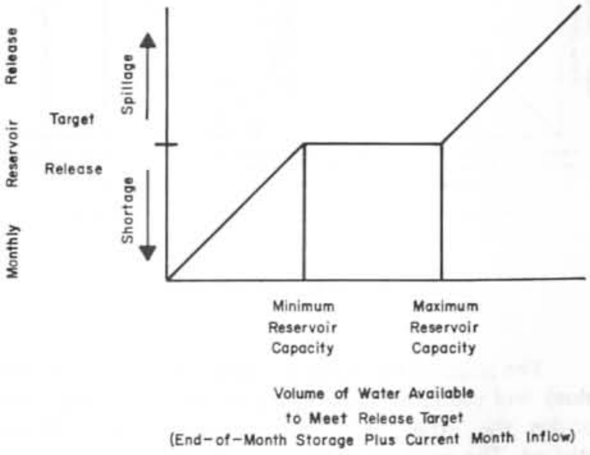
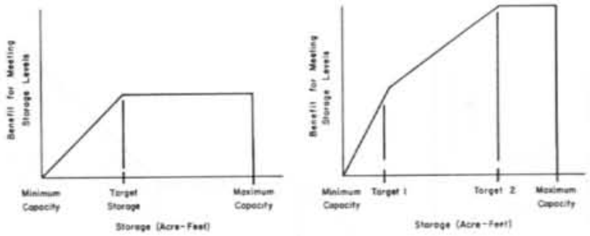


Figure 5. Monthly Reservoir Release Rule

This method is attractive in that monthly releases can be adjusted to the level of demand. However, it is much less flexible in a multireservoir system where water may be moved from one storage location to another and thus demands can be satisfied by other system reservoirs depending upon the total storage in the entire water resource system.

The third method provides an attractive alternative because neither reservoir storage levels nor reservoir releases are fixed; instead, desired storage levels compete with the value of water for satisfying demands. Figure 6a demonstrates a possible realtionship between storage levels and benefit for maintaining storage that could be used in this method. These benefits can either be related empirically to the economic benefits derived from different reservoir storage levels or can be assigned values that result in efficient operation of the system based on minimizing system total cost (excluding capital cost). In the first case, economic benefits for maintaining certain storage levels accrue from recreation, power generation, flood control, and fish and wildlife consideration. For the purposes of this research, these benefits are considered as a "desire" or "priority" for maintaining certain reservoir levels and are not derived as benefits in strict economic terms. Using this relationship, the benefits for meeting storage requirements increase linearly until the target storage level is reached. At this point the curve flattens and excess water may be stored up to the reservoir maximum capacity but with no increase in benefits due to storage maintenance.

Although not incorporated in the presently developed rules, a logical extension is to develop nonlinear benefit-storage curves such as shown in Figure 6b. This type of relationship puts greater value upon the satisfaction of the first target storage level and gradually lowers the importance of subsequent storage increments.



A. Two-Step Benefit-Storage Curve

B. Multi-Step Benefit-Storage Curve

Figure 6. Benefit-Storage Curves

The slope of the benefit-storage curve (unit benefit value) and the cost of delivering water to the reservoirs decides the order in which storage targets will be satisfied. The method is, however, limited by the ability to develop suitable storage targets and unit benefit costs.

It is method 3 that is developed in this research; it requires the application of the allocation model to develop meaningful storage targets based on minimum system operational costs (including penalties) and the subsequent use and refinement of these storage targets in the multibasin simulation and optimization model.

Modifications were made to both the allocation model and the simulation-optimization model (SIM-III) to make them suitable for the development and application of this type of reservoir operating rule. AL-III, the latest version of the allocation model, incorporates the capability to set storage target levels and benefit values for meeting these storage levels in the system reservoirs for the last month in the multiyear period being evaluated.

This capability was included in the model by the introduction of parallel interseason storage arcs in the network representation of the physical configuration. Figure 6a shows two segments of a benefit-storage relationship that correspond to the two arcs. The first arc has a lower bound equal to the minimum reservoir storage level and an upper bound of the target storage level for that season; an estimated benefit value is specified as input data. The second arc allows for storage up to the capacity at no additional benefit. The latest version of the simulation-optimization model (SIM-IV) has been similarly modified and uses two parallel storage arcs in a similar fashion to accommodate end-of-month storage targets as illustrated in the benefit-storage curve of Figure 6a. Since both the AL-III and SIM-IV models optimize water transfer on the basis of minimizing costs, benefits (negative costs) must be specified for meeting the target storages. However, as mentioned previously, these benefits are actually priorities for meeting storage levels and are assigned on a rational basis related to the desired operation of the system. They function in an analogous manner to the penalty costs used to drive the models to meeting demands (see Reports 118 and 131). The next step in operating rule development would be to relate storage levels to their actual value for multiple purposes. For example, storage benefits may be assigned based upon the estimated economics of recreational use and/or power generation of a particular reservoir. If these uses are more economically beneficial than meeting certain irrigation requirements, then maintaining storage would have a higher benefit than meeting the latter demands. The converse situation will also occur; municipal and industrial demands will generally have a higher priority (and benefit) than maintaining reservoir storage.

The procedure which follows is designed to develop reservoir operating rules based upon a criterion of minimum total cost (shortage penalties plus operation and maintenance costs) for the entire water resource system considering *only* meeting demands for water. If the reservoir operating rules are to be set based upon the economic benefits accruing to storage from recreation, power generation, etc., an economic analysis must be performed to permit relating these benefits to the penalties assessed for not meeting demands, the costs of pumping, etc. When this has been accomplished the storage benefits can be directly used in the optimization procedure and steps 1 and 2 of the following discussion may be omitted.

## Development of Reservoir Operating Rules

The procedure for development of reservoir operating rules is divided into five separate steps. These are:

1. Simulate the specified system with the allocation model to generate optimal storage levels using a system minimum operation cost criterion (including shortage penalties).

2. Develop storage plots from the simulation which show storage levels in years of shortage and spilling.

3. Establish initial target storage levels, benefit values for storage in each reservoir, and check their effect on system performance in the simulation-optimization model.

4. Modify the operating rules using the simulation-optimization model having more refined cost estimation procedures (SIM-IV).

5. Finalize target storage levels and benefit values.

To develop the initial operating rules for the example water resource system, the historical hydrologic sequence and stochastic demands developed in Report 131 (Texas Water Development Board, 1971) were used. The demands were those of the final step in the demand buildup sequence—the ultimate projected demands on the system. It is recognized that, from a theoretical basis, it would be desirable to perform this analysis for a number of generated hydrologic sequences and perhaps for various levels of stochastic demands. However, analysis of this type would be extremely expensive and time-consuming for a probably rather modest improvement in operating rule efficiency. The basic purpose of these operating rules is to permit a reasonably realistic simulation of the prototype system and not to develop rules for all situations, which likely are impossible to define due to the stochastic variability inherent in the supply and demand.

### Step One - Simulate System With Allocation Model (AL-III)

The allocation model spans a multiyear period—up to four years in one-year increments—and, as a result, it simulates the system operation with near perfect (four years ahead) foresight of hydrology and demands. Thus, storage levels that result for each reservoir are consistent with the minimum total cost operational plan for the system. The allocation model cannot be realistically used in a final evaluation of the water resource system response because of the perfect foresight assumption. However, the total operation costs developed with such an optimal allocation can be used as the cost objective to be achieved with the simulation-optimization model (SIM-IV) and its operating rules, because this model uses only current-month hydrology and demands which would be available to the water system operating entity.

Since the perfect foresight characteristic of the allocation model is unrealistic, any reduction in the length of time into the future assumed to be known is valuable. As a first step towards reducing the amount of foresight implied by a four-year analysis, the allocation model is executed using one-year foresight with target storage levels at the end of each year of simulation. These targets are associated with the desired level of carry-over storage between water years. The desired level of carry-over storage between years is that volume of water which minimizes the water shortages in succeedinng years. Another reason for reducing the AL-III foresight to one year is because the operating rules to be derived from this technique are to be monthly rules, which remain the same for each specific month for all years. This repetition of the monthly rules is necessary because monthly rules which vary from year to year imply foresight of hydrology and demands. This foresight is not applicable in the real physical case or in the SIM-IV simulation model which operates on a month-to-month basis.

A measure of the success of the annual carry-over storage level targets is how close the resulting operational costs are to the minimum-cost objective established in the multiyear optimization. If the operational costs do not approximate the minimum cost, new estimates of annual carry-over storage targets are made, and the new targets are evaluated. This procedure is continued until the operational costs approximate the minimum-cost objective. At this point, Step One is concluded. The results of this step are storage levels for each month and each reservoir, and annual carry-over storage targets for each reservoir.

It is important to note that because the system is normally under-constrained the results may not be unique. In other words, there may be alternative combinations of reservoir storage levels that result in the same total system cost. In the interpretation of these results, it is also important to note that in the allocation model, as developed in this research, evaporation losses are not a function of storage level. This shortcoming can lead to unnecessarily high storage levels in areas that have high evaporation rates.

### Step Two - Develop Storage Plots

Step Two involves the use of the results from the first step to develop envelopes of storage plots for years in which surplus waters were spilled from the system and for years in which shortages were incurred. Figure 7 illustrates example envelopes of this type of reservoir storage plot. If the reservoir storage could be maintained along the envelope of *maximum* storage levels that occurred during years of shortages, demands would have a high probability of being satisfied. In other words, this envelope describes a reservoir operational pattern that would minimize water shortages. The envelope of *minimum* storage levels that occurred during years of system spillage describes the highest levels at which a reservoir can be maintained without risking the chance of spilling surplus inflows. This envelope represents an operational pattern that would minimize system water spillage.

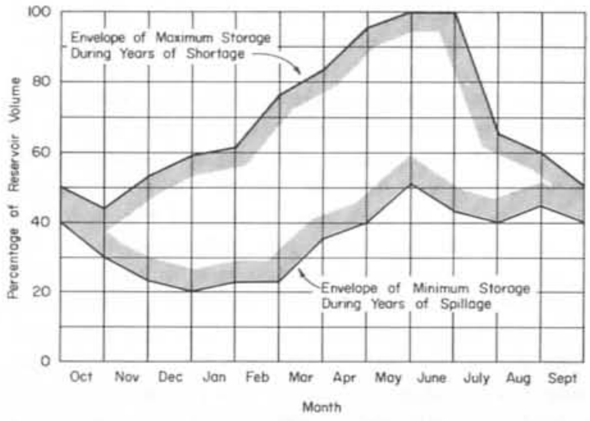


Figure 7. Typical Storage Plots

Where the storage targets are set between these two envelopes depends upon the inflows to and the demands from the reservoir since (1) the closer the targets are to the upper envelope the greater the risk of spillage, and (2) the closer they are to the lower envelope the greater the probability of shortages being incurred. It must be reiterated at this point that the technique being described is designed to provide operating rules which minimize system cost while minimizing water shortages. The benefits accruing to various storage levels are derived from the capability of the system to meet demands and not from any other criteria. The goal, of course, is to find storage targets that, when used in SIM-IV, will predict the same shortages and spills that were predicted by the allocation model. (It is possible that shortages would be reduced because SIM-IV predicts evaporation losses more accurately than AL-III.)

In addition to providing information for setting storage targets, these plots indicate some general operational characteristics of the reservoirs. If the two envelopes are very far apart, this indicates the reservoir is probably not too important in reducing either spills or deficits and the targets should be set primarily to minimize storage fluctuations. A careful analysis may in fact indicate that the reservoir is not necessary for proper functioning of the system. On the other hand, when the two envelopes are close to one another the reservoir is probably critical to the performance of the system and the storage targets should be set very carefully. If the condition occurs where the minimum storage envelope for spillage exceeds the maximum storage envelope for shortages, this means the reservoir is critical but that targets can be set anywhere within the range. The logic behind this analysis is as follows: if the system is experiencing a year in which some demands for water cannot be met (shortages), it follows that to minimize the shortages the reservoir storages throughout the year should be maximized, implying a maximum availability of water to meet demands. Conversely, in wet periods in which water must be spilled from the system it is desirable to maintain the reservoirs at the lowest possible levels to maximize the quantity of water captured. A wide gap between the two envelopes simply indicates an insensitivity of system demands and system spills to the storage in the particular reservoir. A narrow gap or reversal of position of the two curves indicates a progressively more sensitive relationship.

At the conclusion of this step the reservoirs should be characterized by their envelopes of minimum and maximum storage, their local demand-inflow ratio, and their relative importance to the system operation. This analysis provides the basis for setting "benefits" for maintaining storage in selected reservoirs based on a system minimum-cost criterion considering meeting system demands as the most beneficial use of water.

### Step Three - Establish Initial Rules

From the two envelopes shown on the storage plots, initial storage target levels are determined using the reservoir's demand-inflow ratio as a guide. If this ratio is high, targets are set initially along the envelope of maximum storage to minimize shortages. For reservoirs with a low ratio of demands to inflows, the initial targets are set along the minimum storage envelope to minimize spills. In the case of reservoirs whose inflows are about the same as their demands, initial targets are set midway between the two envelopes with a smooth seasonal pattern.

Next, benefit values for storage in each reservoir must be set to complete the data requirements of the rules. The two possible bases for such costs are (1) evaluate the economic value of water in the reservoir for future uses, and (2) set the values based upon the priorities of reservoirs to meet the demands in the system. The first alternative requires a detailed economic analysis to place system operating costs, benefits for meeting demands, and benefits for maintaining storage on a consistent basis. This would be the method of choice in the detailed planning of a surface water resource system. Because this information was not available for this research and the example problem, the second alternative was used.

The basic procedure for setting storage benefits is to identify the system locations at which the greatest shortages occur during the simulation period and to then develop a benefit structure which, after allowance for pumping costs, will result in the withdrawal of water from reservoirs in the order of their importance in terms of meeting system demands. Thus, reservoirs that are most important should be assigned the greatest benefit value for achieving the target storage level. This procedure is analogous to the technique for establishing priorities for storage in the SIMYLD-II model, which was discussed in Chapter II. However, in the case of AL-III and the simulation-optimization models, SIM-II and SIM-IV, an actual "value" is assigned to the benefits accruing from meeting a desired (target) level of storage in a specific reservoir. These values are analogous to the negative benefits (penalty costs) assigned for not meeting demands. The magnitude of the benefit assigned determines how hard the optimization model tries to meet the specified target storage. Although as discussed above, insufficient information may be available to actually calculate benefits for storage, the benefits assigned by the analyst can reflect his judgment of the relative priority between competing uses subject to the major consideration of meeting demands at a minimum cost. Meeting target storages in the reservoirs which dominate the operation of the system (major storage reservoirs) will be assigned a greater benefit than meeting storage in the smaller, less significant reservoirs. Another factor which can be considered in assigning the benefits for meeting desired storage is the expected level of recreation and fish and wildlife use in the various reservoirs. A reservoir with anticipated high recreational use would have a relatively high benefit assigned for storage maintenance. Similarly, the analyst should consider factors such as the local demands on the reservoir, flood control storage required, and environmental effects when developing the benefits to be assigned to the target storages for each reservoir in the water resource system. However, without actual economic information, this type of benefit assignment is very approximate.

After benefit values and storage targets have been assigned, the system is simulated using a version of the simulation-optimization model (SIM-III) which operates on the same reservoir benefit and cost structure as the allocation model (as described above). It also uses the same fixed levels of evaporation. The total costs and system response associated with this simulation are then compared with the allocation model costs. In areas of the system where the response is inconsistent with the original allocation response, the targets and benefit values must be realigned to give better results. It is probably impossible to achieve costs that are exactly the same as from the allocation model and, as a result, this process of refinement should continue only as long as the returns from adjustments in storage targets or benefits are significant. At the conclusion of this step, a set of monthly operating rules is available that produces, in the simulation-optimization model, system performance and costs that are comparable with the results produced by the allocation model with its look-ahead capability.

### Step Four - Modify Operating Rules

The modified set of targets and benefit values are next used in the SIM-IV version of the simulation-optimization model that uses unit pumping costs and evaporation based upon actual monthly storage levels calculated during the simulation rather than from estimated storage levels as used in the allocation model. The performance and operating costs of the system are reevaluated based on the result of the improved simulation and cost estimation. In particular the quantities evaporated and spilled are examined to see if modification of the rules could potentially improve system performance. The targets may also be modified to keep reservoirs that have high evaporation rates as empty as possible and to keep reservoirs that spill empty at periods preceding high inflow seasons if this is found to improve system operation. These changes must, however, not change the fundamental operating pattern of the system. Step Four will require a number of simulations before changes in target levels will not make a significant improvement in total operating cost. At the conclusion of this step, a set of operating rules will be available that will produce an operational pattern that approximates the minimum-cost operation of the system. (Due to changes in evaporation quantities and unit pumping costs, the system costs will not be directly comparable to allocation model results.)

### Step Five - Finalize Individual Reservoir Operating Rules

The final stage in the development of operating rules is to refine the target storages for each reservoir to improve the response to local demands for recreation and other amenities. These adjustments must be made subject to the conditions that they do not cause an unacceptable change in the total cost for the system as a whole. If a change of unacceptable magnitude occurs, this condition is tantamount to a complete redefinition of the objectives of the supply system. The objective of this step is primarily to improve the operational patterns of the reservoirs without increasing system operating costs. This step is feasible since, as pointed out earlier, the results of the optimization problem are not unique. When an acceptable operational pattern is achieved, the procedure is complete and the reservoir operating rules are established.

## An Example Problem

The Trans-Texas Division of the Texas Water System as illustrated in Figure 8 was used as an example problem to test the procedure. The reservoir and canal capabilities were designed to meet the expected 1990 levels of demand. The historical hydrologic sequence described in Report 131 (Texas Water Development Board, 1971) was also used in this example.

### Step One - Simulate System With Allocation Model

Table 1 summarizes the cost results at five-year intervals for a 35-year simulation using the allocation model with three-year forecasting capability. Three-year forecasts were used to reduce analysis costs and, since the length of the most critical droughts in the historical sequence was three years, no additional advantage could be obtained by use of four-year forecasting.

These results represent the costs derived from operating the system with essentially perfect foresight of water supplies and demands. For the purposes of this example only reservoirs 1, 2, and 4 were analyzed although all 12 reservoirs should be similarly treated in an actual planning analysis.

### Step Two - Develop Storage Plots

Figure 9 shows the storage plots derived by plotting the envelopes of storage levels in years of shortage and years of spillage for reservoirs 1, 2, and 4.

### Step Three - Establish Initial Rules

Reservoirs 1 and 2 have very high demands with virtually no local inflow and therefore the maximum storage envelopes based upon years of shortage were used to set inital targets. Reservoir 4 is in an area where most of the system inflow occurs with very small demands and thus the minimum storage envelope in years of system spilling was used to set initial target storage levels. Table 2 shows the reservoir target storage levels and fraction-full for each month as derived from the storage plots.

A cursory analysis of the initial target storage values indicates that it may, after further analysis, be possible to reduce the sizes of reservoirs 1 and 4 by 31 percent and 10 percent, respectively.

Based upon their location in the system the reservoirs were assigned benefit values for storage. Reservoirs 1 and 2 are the prime supply locations, and consequently were assigned the highest storage benefit values. No benefits were assigned to storage for meeting any uses other than system demands. For the three

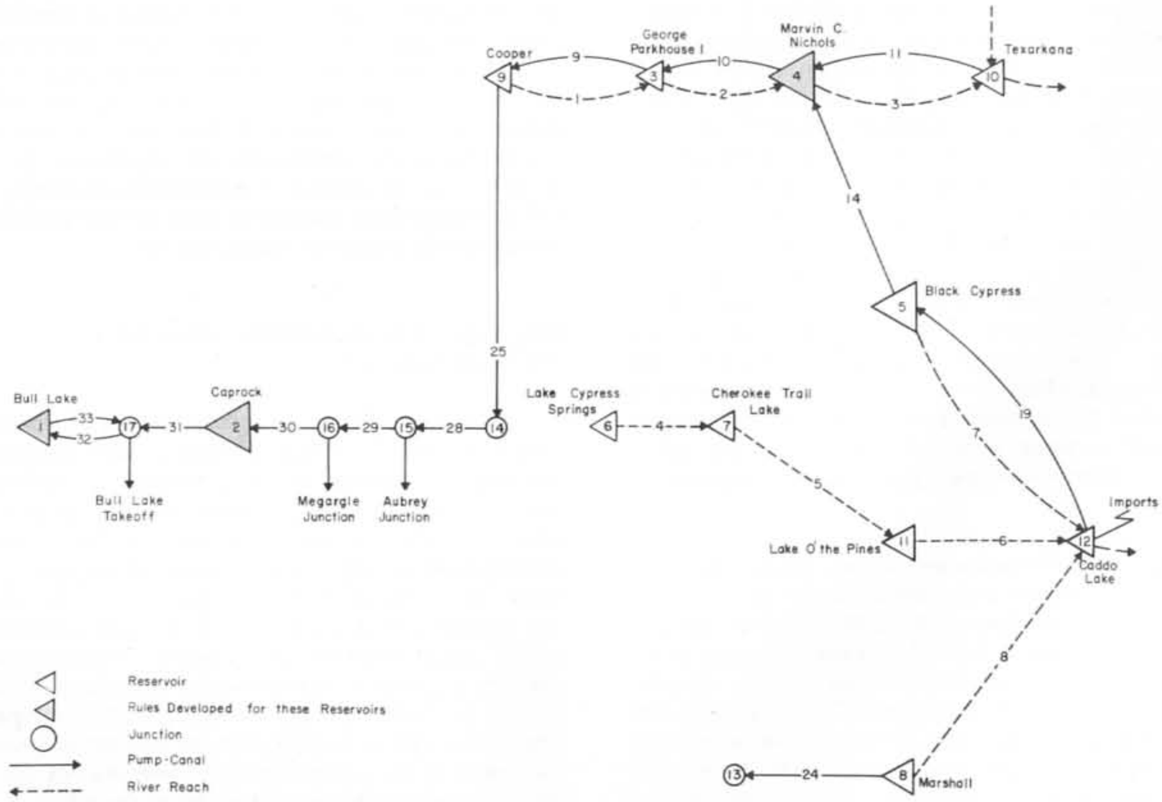


Figure 8. Configuration of the Example System Used in Formulating Reservoir Operating Rules

## Table 1.—Cost Results from the Allocation Model
## Three-Year Forecasts, Historical Hydrology

| Year | Total Power Costs (Thousands of dollars) | Total Shortage* Costs (Thousands of dollars) | Power + Shortage Costs (Thousands of dollars) |
|---|---|---|---|
| 5 | 171,325 | 156,300 | 327,625 |
| 10 | 320,985 | 577,100 | 895,085 |
| 15 | 471,387 | 577,800 | 1,049,187 |
| 20 | 649,469 | 577,800 | 1,277,267 |
| 25 | 827,415 | 937,400 | 1,764,815 |
| 30 | 979,777 | 1,398,700 | 2,378,471 |
| 35 | 1,131,190 | 1,516,700 | 2,647,890 |

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* based on $100 per acre-foot of shortage.

## Table 2.—Initial Target Storage Values

| Month | Bull Lake Reservoir 1 | | Caprock Reservoir 2 | | Marvin C. Nichols Reservoir 4 | |
|---|---|---|---|---|---|---|
| | Storage (Thousands of acre-feet) | Fraction-Full | Storage (Thousands of acre-feet) | Fraction-Full | Storage (Thousands of acre-feet) | Fraction-Full |
| Oct. | 1,100 | 0.69 | 300 | 0.20 | 1,340 | 0.55 |
| Nov. | 1,100 | .69 | 540 | .36 | 1,240 | .51 |
| Dec. | 1,100 | .69 | 780 | .52 | 1,130 | .46 |
| Jan. | 1,100 | .69 | 1,040 | .69 | 950 | .39 |
| Feb. | 1,100 | .69 | 1,280 | .85 | 1,050 | .43 |
| Mar. | 1,100 | .69 | 1,420 | .95 | 1,490 | .61 |
| Apr. | 1,100 | .69 | 1,500 | 1.00 | 1,660 | .68 |
| May | 620 | .39 | 1,500 | 1.00 | 2,170 | .89 |
| June | 510 | .32 | 1,500 | 1.00 | 2,210 | .90 |
| July | 400 | .25 | 1,380 | .92 | 2,210 | .90 |
| Aug. | 260 | .16 | 620 | .41 | 1,850 | .76 |
| Sept. | 330 | .21 | 150 | .10 | 1,440 | .59 |

reservoirs, the following benefit values were assigned:

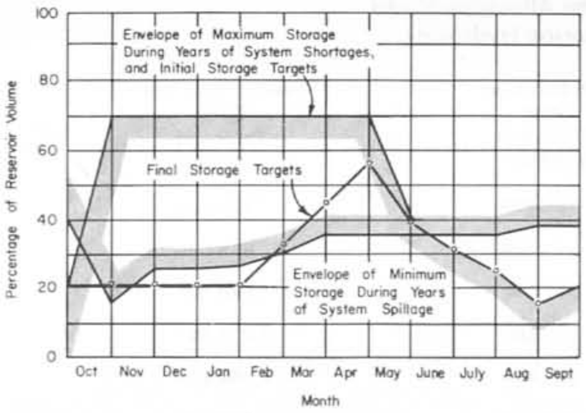
| | |
|---|---|
| Reservoir 1: | $50 per acre-foot, |
| Reservoir 2: | $50 per acre-foot, and |
| Reservoir 4: | $26 per acre-foot |

It should be noted that in the test problem shortage penalties (penalties for not meeting demands) were set at $100 per acre-foot and thus, at no time will the system store water in preference to meeting the demands. This is in keeping with the basic assumption of the example problem that all demands will be met when possible. For other reservoirs in the system the operating rules were selected on the basis of minimizing pumping costs and rapid fluctuations in storage levels. No attempt was made to assign values to other uses of stored water.

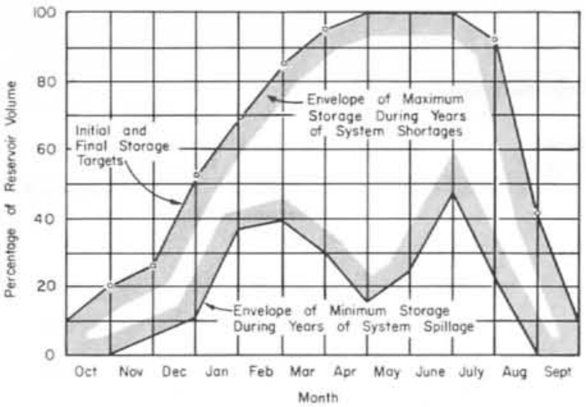
To simplify discussion of the procedure, the comparison of performance for the end-of-year target values and the comparisons using SIM-III will be omitted. Instead, the process of refinement using SIM-IV will be discussed in detail.

### Step Four - Modify Operating Rules

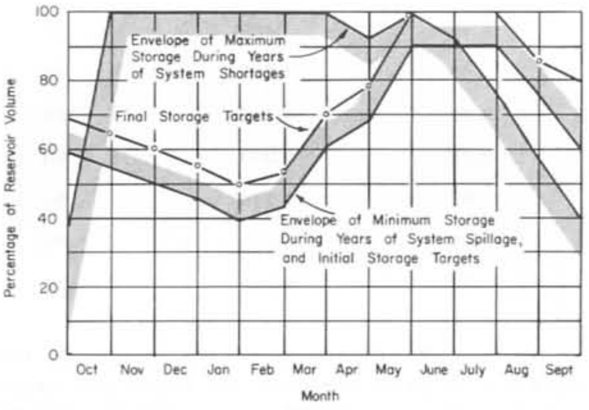
This step requires numerous simulations with SIM-IV to improve and refine the operating rules. Table 3 lists the simulations made and the significant changes in each, and Table 4 summarizes the costs and other relevant results. The base case, Run 0, provided a cost result with the fixed minimum storage rules that were used in SIM-III prior to the development of this



a. Bull Lake (Reservoir 1)



b. Caprock (Reservoir 2)



c. Marvin C. Nichols (Reservoir 4)

Figure 9. Storage Plots

procedure and SIM-IV. As such, it provides a basis upon which this procedure can be evaluated. Run 1 used the target storage levels derived directly from AL-III for reservoirs 1, 2, and 4. The improvement in system operation is noticeable in the reduced shortage penalty costs and evaporation losses. There was, however, an increase in spills from the system.

**Table 3.—Summary of Cases Studied**

| | | |
|---|---|---|
| Run | 0 | Base case using rules of Report 131 |
| Run | 1 | Target storages from AL-III |
| Run | 2 | Adjusted target storages to reduce filling rate in reservoir 1 |
| Run | 3 | Modified target storages to reduce evaporation in reservoir 1 |
| Run | 4 | Increased target storages in reservoir 1 |
| Run | 5 | First decrease of target storages in reservoir 1 |
| Run | 6 | Second decrease of target storages in reservoir 1 |
| Run | 7 | Decreased target storages in reservoir 2 |
| Run | 8 | Increased target storages in reservoir 2 |
| Run | 9 | Increased target storages in reservoir 4 |
| Run | 10 | Decreased target storages in reservoir 4 |
| Run | 11 | Second increase of target storages in reservoir 4 |

In Run 2 the target storages were adjusted for reservoir 1 to slow its filling rate; these targets were further adjusted in Run 3 to delay the start of filling but to allow the peak to be reached at the same time. Runs 4, 5, and 6 were made to test the cost sensitivity to changes of time of filling and adjustments to peak target storage in reservoir 1. Run 4, which had increased target storages in reservoir 1, showed no improvement in cost, while Run 5, which had decreased target storages, indicated a reduction in cost. However, with target storages further decreased in Run 6, cost again rose. As a result the target storage levels from Run 5 were selected for reservoir 1. Runs 7 and 8 involved a similar test for reservoir 2. In both cases costs rose which indicates the initial storage targets were best.

Finally, Runs 9, 10, and 11 tested variations in the target storages for reservoir 4. From this series of simulations Run 9, which had slightly increased storages, provided the lowest cost. Table 5 lists the final storage targets that resulted from this series of runs. It is significant to note that the major change in target storages from those derived from AL-III is in reservoir 1. Poor estimation of evaporation losses in AL-III is the primary cause of poor initial storage targets. If the allocation model had a better procedure for estimating evaporation losses, better initial storage targets would have resulted from Step Three.

As presently constituted the allocation model does not take reservoir storage levels into account in its estimate of evaporation losses in the optimization process and, as such, allows early filling of reservoirs even though they may have high evaporation rates and corresponding high losses of water. For the particular example investigated, evaporation was extremely important and dominated the selection of operating rules for reservoir 1.

### Table 4.—Example Problem Cost Results

| Run | Evaporation (Thousands of acre-feet) | Spills (Thousands of acre-feet) | Total Power Cost* (Thousands of dollars) | Total Shortage Cost* (Thousands of dollars) | Total Cost* (Thousands of dollars) |
|---|---|---|---|---|---|
| 0 | 9,742 | 15,611 | 2,484,093 | 1,644,005 | 4,128,098 |
| 1 | 7,658 | 16,344 | 2,465,925 | 1,503,227 | 3,969,152 |
| 2 | 7,328 | 16,649 | 2,438,077 | 1,500,625 | 3,938,702 |
| 3 | 6,522 | 17,503 | 2,362,738 | 1,505,329 | 3,868,067 |
| 4 | 6,638 | 17,433 | 2,387,717 | 1,510,630 | 3,898,347 |
| 5 | 6,305 | 17,878 | 2,336,697 | 1,521,128 | 3,857,925 |
| 6 | 6,350 | 17,779 | 2,349,240 | 1,515,830 | 3,865,070 |
| 7 | 6,138 | 18,217 | 2,350,835 | 1,539,328 | 3,890,163 |
| 8 | 6,885 | 17,044 | 2,390,083 | 1,496,527** | 3,886,510 |
| 9 | 6,268 | 17,885 | 2,335,952** | 1,518,028 | 3,853,980** |
| 10 | 6,422 | 17,900 | 2,336,543 | 1,537,528 | 3,874,071 |
| 11 | 6,311 | 17,857 | 2,336,878 | 1,519,327 | 3,856,205 |

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* All costs are the sum of annual costs for the 35-year simulation period.

** Minimum respective costs obtained.

### Table 5.—Final End-of-Month Target Storage Values

| Month | Bull Lake Reservoir 1 | | Caprock Reservoir 2 | | Marvin C. Nichols Reservoir 4 | |
|---|---|---|---|---|---|---|
| | Storage (Thousands of acre-feet) | Fraction-Full | Storage (Thousands of acre-feet) | Fraction-Full | Storage (Thousands of acre-feet) | Fraction-Full |
| Oct. | 336 | 0.21 | 300 | 0.20 | 1,593 | 0.65 |
| Nov. | 336 | .21 | 540 | .36 | 1,495 | .61 |
| Dec. | 336 | .21 | 780 | .52 | 1,372 | .56 |
| Jan. | 336 | .21 | 1,035 | .69 | 1,201 | .49 |
| Feb. | 528 | .33 | 1,335 | .85 | 1,299 | .53 |
| Mar. | 720 | .45 | 1,425 | .95 | 1,740 | .71 |
| Apr. | 912 | .57 | 1,500 | 1.00 | 1,911 | .78 |
| May | 624 | .39 | 1,500 | 1.00 | 2,426 | .99 |
| June | 512 | .32 | 1,500 | 1.00 | 2,450 | 1.00 |
| July | 400 | .25 | 1,380 | .92 | 2,450 | 1.00 |
| Aug. | 256 | .16 | 615 | .41 | 2,107 | .86 |
| Sept. | 336 | .21 | 150 | .10 | 1,691 | .69 |

It should also be noted that shortage costs have a significant effect upon the optimum operating policy and that the best operating policy does not necessarily minimize shortages. This fact indicates that for this specific system operating costs can become so high that even when using a unit penalty cost of $100 per acre-foot it is still more economical to take shortages than to pump water to the irrigation service area. The discussion of the dynamic economic simulation technique in this report (Chapter IV) covers this subject more thoroughly.

As was first noted in Step Three, Table 2, this analysis shows that it is possible to reduce the maximum storage capacity of Bull Lake by 43 percent and still have the least-cost operation system for meeting the irrigation demands. This is true because evaporation is so significant in this region that significant economic advantage can be gained from storing water in low-evaporation regions and pumping at high rates during the water usage periods.

### Step Five - Finalize Individual Operating Rules

This step was not undertaken in this example problem since it involves modifying the above rules slightly to accomplish secondary system objectives such as recreation, etc. For example, it would be desirable to constrain Marvin C. Nichols Reservoir at a target storage greater than 1 percent full during December to satisfy recreational and fish and wildlife criteria.

Based upon the experience gained in the development and limited application of this procedure, the following conclusions can be drawn:

1. The procedure presented is a rational approach for the determination of reservoir operating rules for complex systems of reservoirs and canals.
2. More experience with systems other than the Trans-Texas Division is needed to further define the criteria used to establish initial target storage levels.
3. Evaporation and varying pumping costs due to reservoir changes should be incorporated in the optimization procedure of the allocation model. Such an improvement would significantly help to define a unique set of rules directly from the allocation model. This enhancement involves fundamental changes in the optimization algorithm used in this model.
4. For the development of realistic operating rules it is necessary to have an economic value established for the benefits of maintaining storage for multiple uses.

# IV. DYNAMIC ECONOMIC SIMULATION

## Introduction

The research conducted prior to 1971 emphasized the modeling of a water capture, transfer, and distribution system. Only minor effort was spent on simulating the demand for water based upon the available supply.

Several different approaches have been employed in the past on irrigation planning models. In Projects I and II and in previous demand analyses, the Board used a simple soil moisture accounting model to calculate the quantity of irrigation water required (Texas Water Development Board, 1971). This model uses a standard operating policy of filling the soil moisture reservoir to capacity whenever it drops below 50 percent of capacity and no economic assessment of demand has ever been considered. Egli (1971) traces the effects that different hydrologic sequences have on the yields of a set of crops in an area using an irrigation policy that calls for filling the soil reservoir whenever it falls below a specified percentage that is different for every time period. Dorfman (1962), Schmer and Trock (1969), Simkins (1968), and Dracup (1966) are among those who use linear programming as a planning tool for determining cropping patterns. While linear programming can be used to solve problems with a large number of variables, it is usually restricted to a static deterministic formulation. Dudley and others (1971) use the output of a simulation-dynamic programming model to determine the optimal acreage of a single crop to irrigate from a reservoir. Windsor and Chow (1970) and Hall and Buras (1961) use dynamic programming to project expected requirements for irrigation water throughout the growing season. These requirements are then used to allocate water to different crops as well as over time. Using a technological function for the crop-yield water-input relationship, DeLucia is able to sequentially run linear programs to track the operation of a farm through a growing season. However, a computer execution time of 90 minutes per simulated year makes it too expensive to be used to examine a large number of alternatives (DeLucia, 1969). Anderson and Maass (1971) simulate a multifarm, multicrop system in which farmers allocate a supply of water to be applied in each time period throughout the growing season. While adaptive, this approach does not consider the stochastic effects of rainfall and evapotranspiration.

It is imperative to obtain a reasonable estimate of demand for and use of water in an irrigation system since it is the justification for the tremendous investment necessary for many large water resource projects like the example problem. Modeling the supply system involves simulation of the design, construction, and operation of a system of physical facilities in the face of the stochastic environment of nature. Modeling the demand for and use of irrigation water entails, in addition to the stochastic variation in precipitation and streamflow, the added dimension of difficulty of predicting behavioral characteristics of the water users which must be introduced into the analysis.

The water that is available to an area in the form of import or natural inflow should be distributed, equitably and economically, among the competing users shown in Figure 10. The users of water, primarily the farmers in this example, have a demand for water that is the result of the complex decision process necessary to operate a farming enterprise. It is further assumed in this study that the farmers are acting rationally but independently to maximize their expected net returns from farming. It is recongized that additional research is needed in the prediction of municipal and industrial water demands and the benefits accruing from them. The emphasis in this project was on determining the relationship between large irrigation demands and the water available from a surface water resource system. Municipal and industrial demands in this analysis and example problem are to be satisfied before any irrigation demands are met.

Under the assumption of rationality, the farmers are adaptive in their strategy (i.e.,they can change their strategy to account for different conditions). For example, if, at spring planting time, the farmer expects to have a plentiful supply of water made available to him throughout the rest of the growing season, he will plant a complement of high water using, high return crops. Conversely, if he does not expect to have much water available, he will plant a greater percentage of his acreage in dryland crops and in lower yield, lower water use crops. He may decide to reduce the total number of acres planted to best make use of a limited supply of water. Also, during the growing season he must be flexible enough to vary his irrigation strategies to account for the different effects that the realized rainfall, transpiration, and evaporation as well as his irrigation decisions have had on each of his crops. The consumption of water affects supply in subsequent periods through the effects of carry-over storage. Obviously, the demand for and the supply of irrigation water are interactive.

When the supply of water is both ample and inexpensive it can be shown that the best strategy is to irrigate liberally and frequently. However, with expensive, limited, or uncertain amounts of water the best irrigation policy is more conservative. Different crops have different responses to the application of irrigation as illustrated in Figure 11. Crop A brings a relatively high return from being grown dryland and the output increases very little as irrigation water is increased. Crop B, on the other hand, has a very low dryland return but responds well to application of

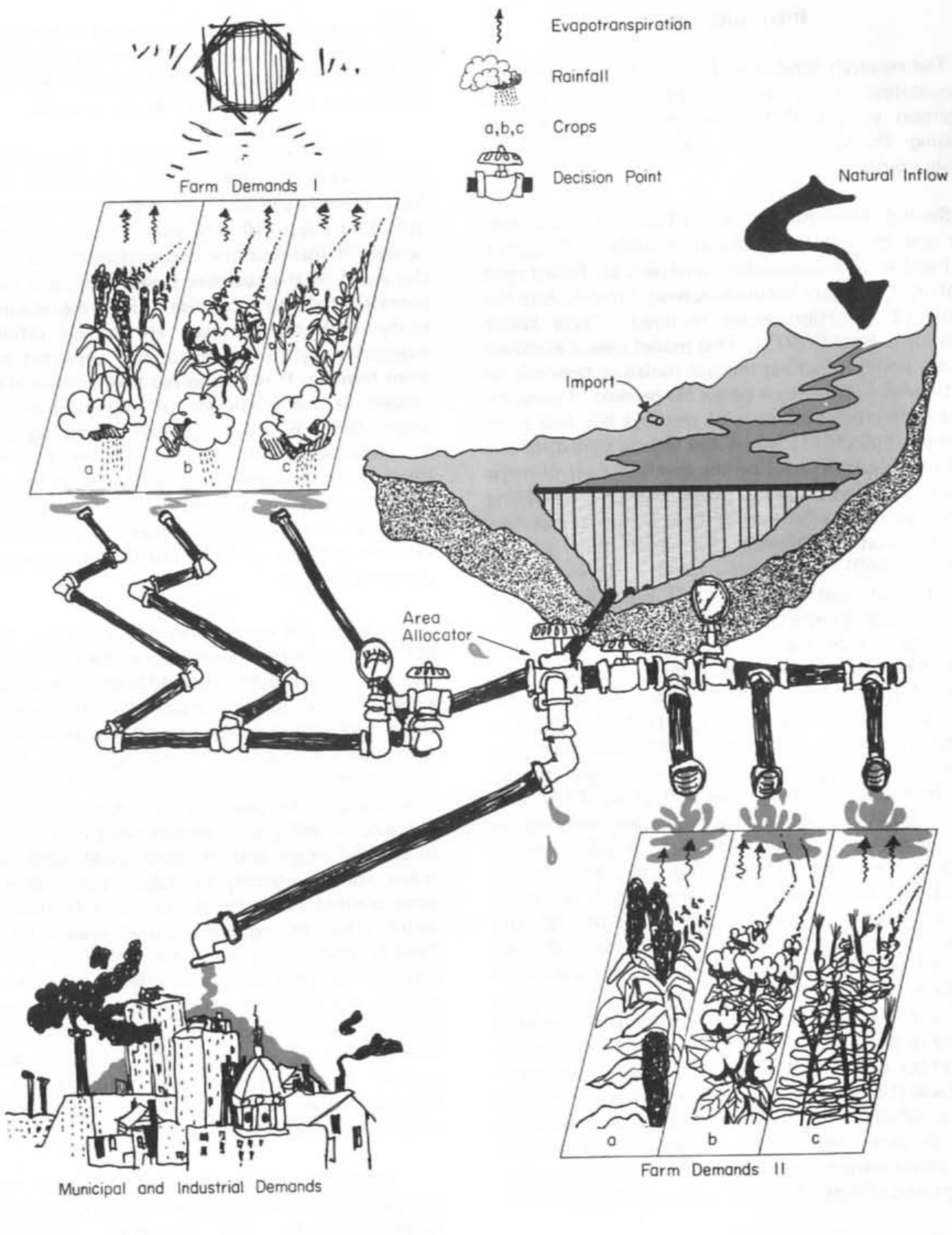


Figure 10

Competing Uses for Available Water From a Typical Surface Water Resource System irrigation water. The functions depicted in this figure are typical of many crops.

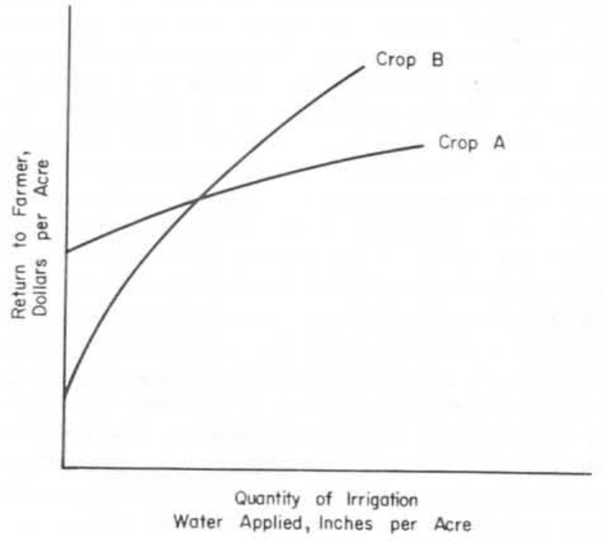


Figure 11. Example of Typical Crop Responses to Increasing Applications of Water

The crop responds to the timing of the irrigation as well as to the quantity of water applied. The amount of water a plant needs varies through the various stages of plant growth and maturation. It is also dependent on meteorologic factors. High temperatures and wind result in a high rate of evapotranspiration (water consumption). Thus, the consumption of water by a plant is related to serveral meteorological factors. Pan evaporation has been shown to be a good factor to use in relating water by consumption to varying climatic conditions. The water a plant uses is extracted from the soil beneath it as shown in Figure 12. Additional water is lost from the soil reservoir by evaporation from the soil pore space. These depletions of soil moisture are counteracted by rainfall and applications of irrigation water. If the soil moisture is allowed to drop below a certain point the crop undergoes stress. When stress occurs the yield of the crop is irrevocably reduced. The amount of damage resulting from stress is dependent not only upon how far the soil moisture is allowed to be depleted but also upon the point in the life cycle of the plant at which stress occurs. In the growth of many crops there are several critical periods during which it is imperative that the water content of the soil reservoir be maintained at a high level to produce satisfactory levels of yield. The classic example is corn during the pre-tassle stage, when even mild stress will cause a significant reduction in output.

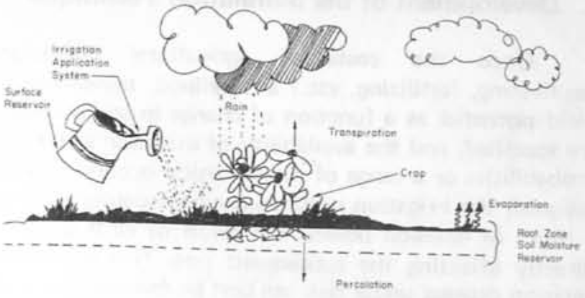


Figure 12. Idealized Diagram of an Irrigation System

The irrigation of a crop is a sequential decision process that is repeated several times during the growing season. Each time a decision is made as to the quantity of irrigation water to apply to the crop the decision is based on several factors. The amount of rain and evaporation expected enters into the decision of the quantity of irrigation water to apply. These values are not known with certainty. However, a range of possible precipitation values and their associated probabilities can be found by analyzing the historical data. For example, for the month of June the probabilities of different quantities of rainfall in the irrigated region of the Texas High Plains are as shown in Table 6.

**Table 6.—Probabilities for Selected June Precipitation Quantities, Texas High Plains**

| QUANTITY (INCHES) | PROBABILITY OF OCCURRENCE |
|---|---|
| 0-2 | 0.35 |
| 2-4 | .45 |
| 4-6 | .15 |
| 6-8 | .05 |

A number of other considerations enter into the typical irrigation decision. If during a particular month there is heavy rainfall and low evaporation, a prudent strategy is to irrigate sparingly to avoid the high expense of surface water supply. Moreover, if at that stage of growth the plant is not affected by stress, there is nothing to gain from irrigation. However, the soil moisture state also affects this decision. If the soil moisture is low and the plant is sensitive to stress, it is best to irrigate in the current month to raise the soil moisture.

The quantity of water a farmer will apply is also a function of its price. The yield potential of a crop is a factor; if a crop has previously been substantially damaged, a liberal application of irrigation water may not be justified when the probable low increase in yield is considered. Finally, one of the more important factors affecting the irrigation decision is the quantity of water available.

## Development of the Simulation Technique

Once the costs of agricultural operations (cultivating, fertilizing, etc.) are defined, transitions of yield potential as a function of change in soil moisture are specified, and the availability of irrigation water and probabilities or a range of meteorlogical occurrences are assigned, the irrigation problem can be decomposed into a series of decision points, the result of each decision directly affecting the subsequent one. This sequential decision process under risk can best be modeled through the use of stochastic dynamic programming (Dracup, 1966). The output of CROP, the dynamic programming model presented herein, is the expected net return and the corresponding optimal decision for every specified period in the growing season (one-month increments in this study) for every possible state of a representative acre of a crop. The state of a unit acre of a crop at any time can be defined by the following three variables:

- soil moisture where probabilities of meteorologic changes for each month in the growing season are supplied by program SML,
- yield potential defined as a percentage of maximum yield attainable under ideal conditions, and
- quantity of irrigation water available for the acre for the remainder of the growing season.

As an example of the type of information generated by CROP, if grain sorghum is at 50 percent of soil moisture and 70 percent of yield potential at the first of July, and 10 acre-inches per acre of irrigation water are available for the remainder of the growing season, the expected net return is $33.27 per acre and the corresponding optimal decision at that time is to apply two acre-inches per acre. Notice that the soil moisture and yield potential states are real states in that they represent measurable characteristics of a crop. The soil moisture can be measured in the field using one of several devices, and the yield potential of a crop can be estimated by the experienced farmer assisted by guidelines from agricultural experts. The quantity of irrigation water available to each crop is, however, an allocation from a higher farm-level decision process. For any combination of the soil moisture and yield potential states, the effect of different allocations of irrigation water to be used over the remainder of the growing season can be investigated and the results presented as in Figure 13. Notice that the term "expected net returns" is used on the ordinate because the occurrence of future rainfall and evaporation cannot be described with certainty but rather as a range of possible occurrences each month with an associated probability. Since dynamic programming works with discrete intervals, the typical output is in the form of points as shown on the curve. The intercept, representing the condition of no available irrigation water, indicates the expected net return from a dryland situation. Notice that the curve flattens at high applications of irrigation water, indicating that there is a limit to the amount of water that can be used beneficially for a given crop. The expected benefit curve varies directly with the price of water as is shown in Figure 14. If the irrigation water is inexpensive, its application will result in a higher net return and thus more water will be applied. A set of these curves, one for each crop, forms the basis for determining the relative worth of allocating water to the various crops on a farm during any period in the growing season. Since these functions generally exhibit decreasing rates of return to increasing water applications, the water available to the farm can be allocated among the crops in a manner that maximizes the marginal returns from the water used and thus guarantees maximuzation of expected returns to the entire farming enterprises. Therefore, a farm return function with the same characteristics as a crop return function can be constructed, as illustrated in Figure 15 for a typical example with crops A and B, of two and three acres respectively, on the farm.

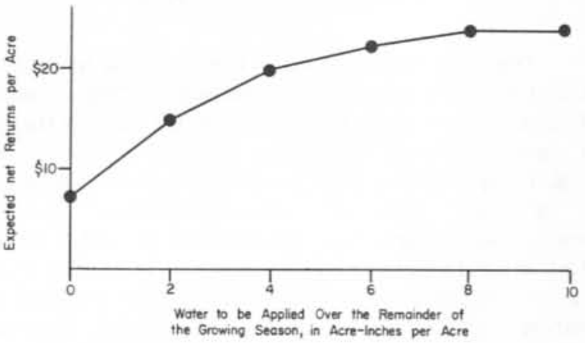


Figure 13. Typical Expected Returns for an Irrigated Crop

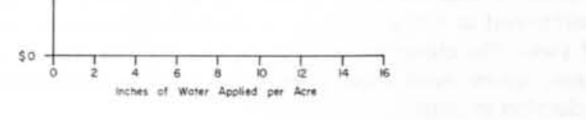


Figure 14. Variation of Expected Net Returns and Water Applied With Unit Cost of Irrigation Water for a Typical Crop

First, the unit acre representation of each crop is multiplied by the number of acres of each crop to obtain

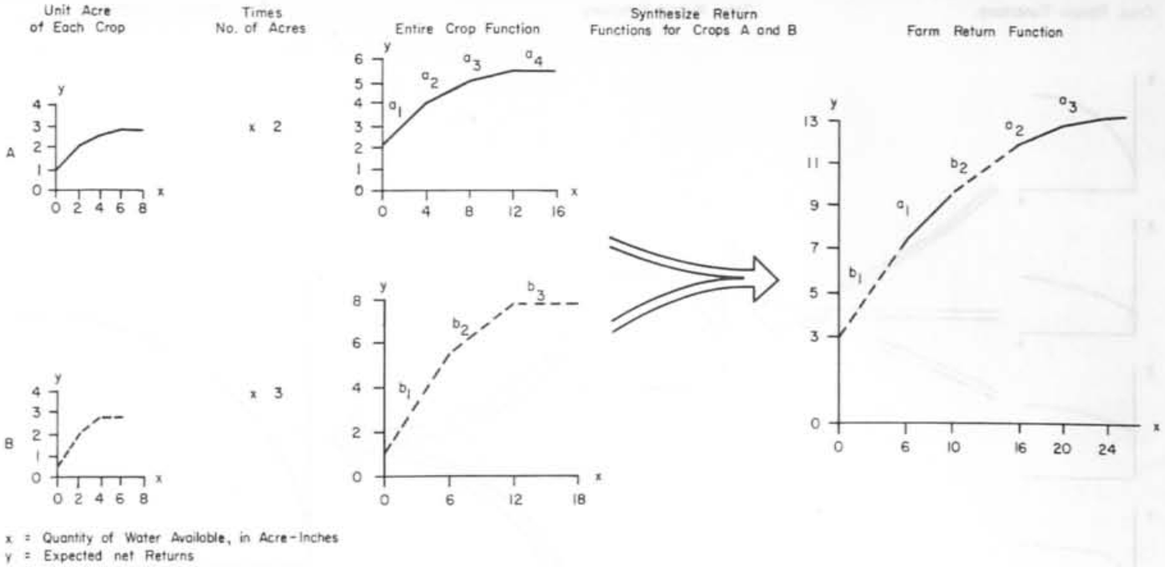


Figure 15. Synthesis of Crop Return Functions Into Farm Return Functions

the return function for the entire acreage of the crop. These are then synthesized into a farm return function by sequentially selecting the highest marginal return (the incremental increase in returns from an incremental increase in water) to water. Notice that the farm return function is built by selecting the steepest portions of the crop functions in order: b1, a1, b2,a2, a3. Associated with each point on each of the return functions is the optimal strategy to follow for the allocation of water at that level. For any availability at the area level, there is associated an optimal allocation to the farms. For this simple example, if 16 acre-inches are available during the example month, 12 acre-inches would be allocated to crop B and 4 acre-inches would be allocated to crop A corresponding to segment $a_1$ on the farm revenue function. Associated with each of these points is the expected return and the corresponding optimal decision of the portion of the total quantity of water allocated to the crop for the remainder of the growing season which should be applied during that month.

Just as the crop return functions can be synthesized into farm functions, the farm functions can be synthesized into area functions as shown in Figure 16. Similarly, this curve has associated with each point on it an optimal allocation of water among farms. Therefore, for a given quantity of water available to an area, the optimal interfarm distribution can be found. It is assumed for this study that the allocation among farms is made in such a manner as to maximize the expected returns to the entire area, not necessarily to the individual farms. This type of allocation is very general in nature and other types of interfarm allocation can be easily considered by making only minor modifications to the modeling system.

The expected return information generated by the dynamic programming model CROP for the planting month is also useful for deciding the relative value of planting each of the crops under consideration for conditions of limited water available to a farm. The planting decision can be modeled by using CRPMX, a linear programming model. In this study, the linear programming model has as its objective the maximization of expected returns to a farming enterprise from planting a complement of crops, with government program restrictions on a limited number of acres, and with limited supply of irrigation water. Since the level of soil moisture affects the dynamic programming solution on which the linear programming problem is based, CRPMX has to consider the existing level of soil moisture at planting time. CRPMX indicates not only the optimal number of acres of each crop to plant, but also the amount of water to allot tentatively to each crop for the remainder of the growing season. It is important to note that since the quantity of water available may change during the growing season, these allocations of water are tentative and subject to revision each time an irrigation decision can be made. The modeling of this adaptive characteristic is a major contribution of this study toward the realistic representation of an irrigation water supply and use system.

The result of this linear programming analysis is the optimal cropping pattern based on a given soil moisture, an expected supply water, and expected net returns per crop. The relative economic attractiveness of the various crops shifts as different amounts of irrigation water are made available. A representative example of the dynamics of this process is shown in Figure 17, illustrating the farmer's adaptive planting decision based upon an estimate of water to be evailable during the growing season. Each point on the farm return function is associated with a crop mix. Because there are several constraints on the problem, parametrically relaxing the

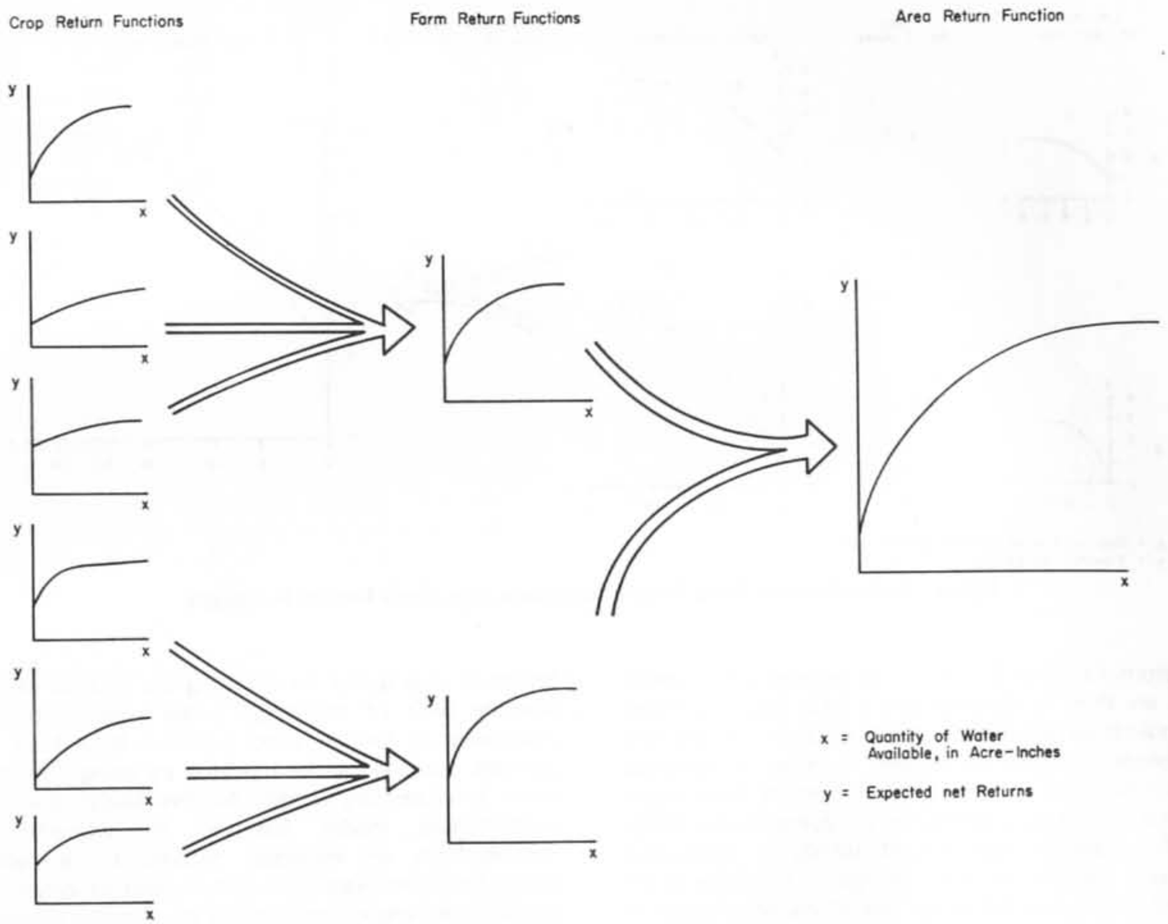


**Figure 16. Two Levels of Return Function Synthesis**

constraint on water available results in a return function that exhibits decreasing marginal returns to water. The entire process being modeled can be depicted by the flowchart on Figure 18 which represents the flow of logic of the dynamic simulation. Note the large number of aspects which are considered. These are:

- occurrences of rain and evaporation (both in terms of realized values as they occur and as a range of projected future alternative values) with corresponding probabilities of occurrence.
- the subsequent effects on the soil moisture and the corresponding effect on the yield potential.
- the planting decisions on several farms based on the conditions existing at planting time.
- the allocation of water to farmers by a higher level distributor.
- the revision in estimates of water availability as information becomes known.
- the allocation of water among crops by rational farmers.
- the intraseasonal allocation of irrigation water to each crop based on the current condition as determined by the past meteorology and decisions.
- the expenditures made by farmers on planting, purchase and application of irrigation water, and the cultural operations performed through the growing season.
- the determination of the yield of the crops at harvest and the corresponding economic return to each of the farmers.

To further illustrate the logic of this dynamic simulation, Figure 19, a schematic diagram of the entire process, is provided. It shows, in simple terms, the decisions which must be made at each point in the growing season and the level at which these decisions occur.

This process is simulated using subroutine ECOP which is a simulation of the demand for water.

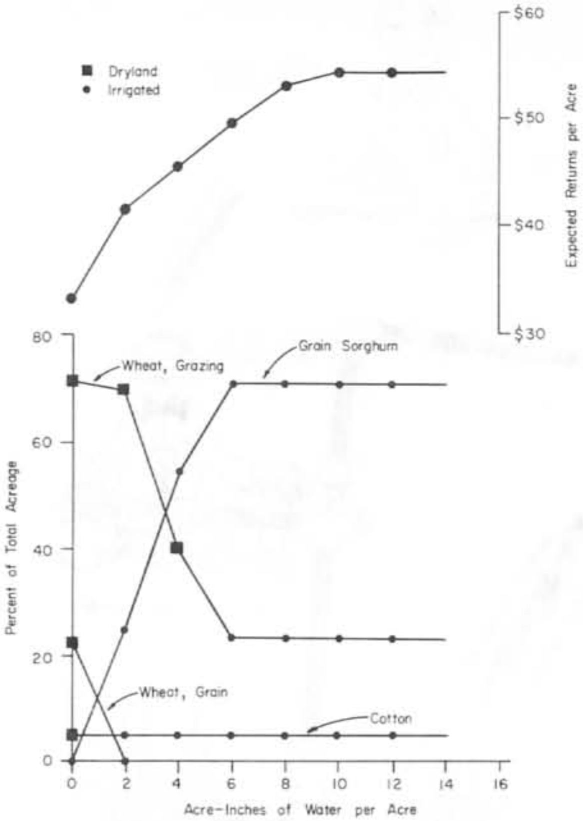


Figure 17. Changing Cropping Pattern for Different Anticipated Seasonal Availabilities of Irrigation Water

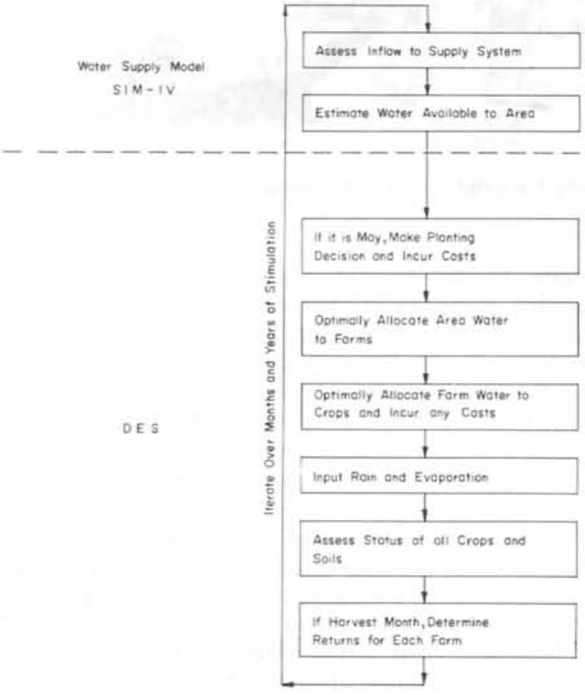


Figure 18. Flow of Process Being Simulated During Dynamic Simulation of an Irrigation System

Subroutine ECOP can be used with the supply model, SIM-IV, to interactively arrive at a time stream of cash flow corresponding to the time stream of input hydrology. The cash flow incorporates the effects of many other factors on the economics of the situation both within and between growing seasons. The entire modeling system can be depicted as shown in Figure 20.

Each month the simulation program, SIM-IV, allocates the water that has flowed into the system reservoirs among the competing demands and, based on historical data, makes an estimate of the quantity of water that will be available for agricultural uses for the remainder of the growing season. This estimate is passed to subroutine ECOP which tentatively allocates the expected supply of water among the various crops on several farms in a manner which maximizes the expected net return to each of the farms. This allocation then specifies a certain application of irrigation water to each crop for the month being simulated. The sum of these applications plus the associated efficiency losses comprise the amount of water actually demanded for that month. This figure is fed back to the supply program, SIM-IV, which then revises the values of the reservoir contents to reflect these withdrawals.

## The Trans-Texas Division—An Example

The Trans-Texas Division of the proposed Texas Water System was briefly discussed in Chapter I of this report. It serves as an excellent, real-world test case for the economic simulation technique developed herein. Additional background information on the problem and an example analysis using DES are provided in the remaining sections of this chapter.

### Summary of the Problem

The Texas High Plains can be divided into two areas, each with reasonably homogeneous characteristics. The northern portion of the plains has the shorter growing season and an average rainfall which is slightly greater than that of the southern region. Also, the predominantly hardland soil in the north permits the use of furrow irrigation. The southern region is composed of a mixed or a sandyland type soil that makes the use of sprinkler irrigation more desirable. In both regions the available supply of ground water in the underlying Ogallala aquifer is being exhausted.

Designing a system to supply water to the Texas High Plains is more difficult than designing most water supply systems. In many irrigation projects the rainfall is so low during the growing season that it can, for most practical purposes, be ignored altogether. In the Texas High Plains, however, a significant amount of rain may fall on the crops during the growing season, but this varies widely from year to year. This variability is due to the fact that most of the rainfall in the High Plains

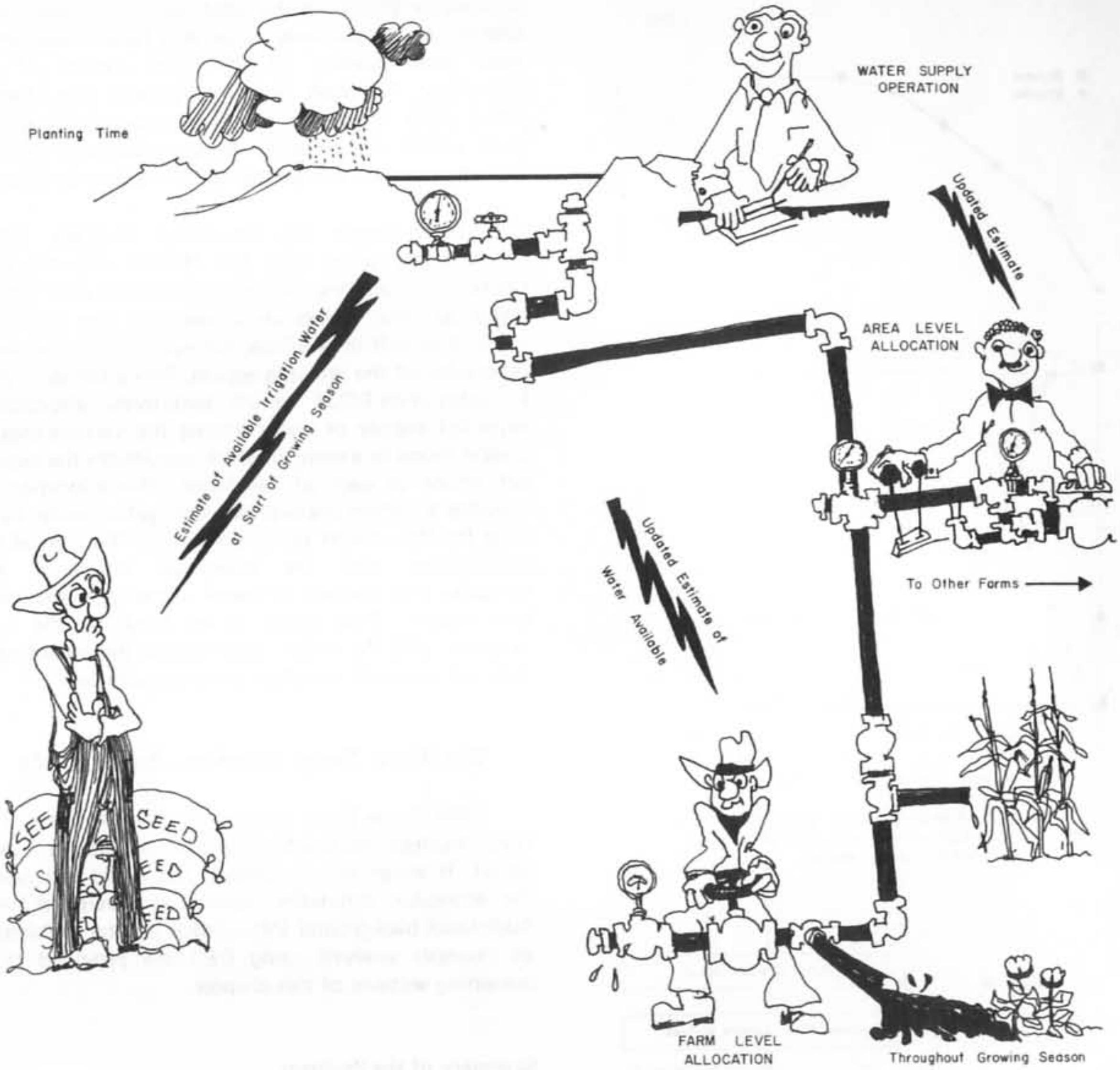
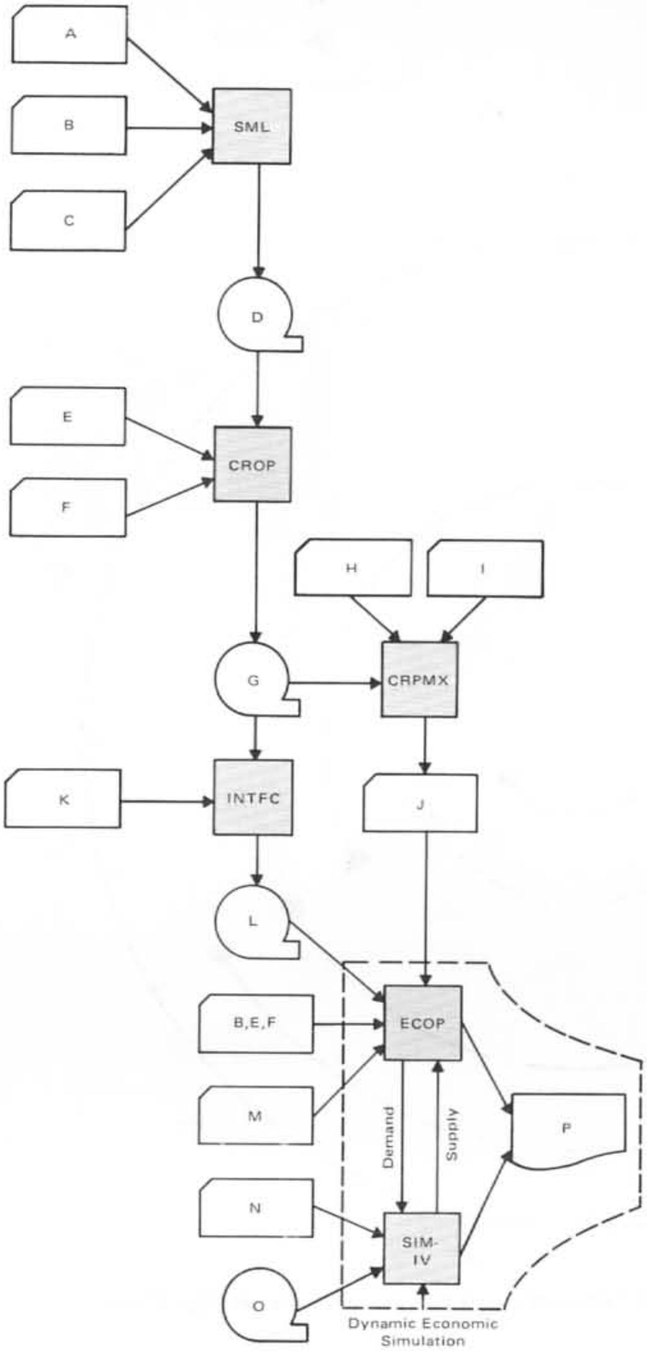


Figure 19. Schematic of the Irrigation Supply-Demand Simulation Process

comes from highly unpredictable thunderstorm activity. For example, the average annual rainfall for Lubbock, Texas is 18 inches, but varies from 4 inches to 30 inches per year. Likewise, because the amount of water actually available to the crops is related to evaporation, it is also highly variable. To further complicate matters, the decision of which crops and how many acres of each to plant in any year has to be made before the amount of seasonal runoff in the East Texas supply basins can be firmly known. In many other irrigation projects most of the water is a consequence of snowmelt, making it rather simple to get reliable estimates of expected supply by measuring the snowpack in early spring.

The candidate crops for planting in the North High Plains are grain sorghum, cotton, wheat for grain, wheat for grazing, and soybeans. In the South High Plains the candidate crops are grain sorghum, cotton, wheat for grain, wheat for grazing, and forage sorghum. The lengths of the growing seasons for these crops are depicted in Figure 21. The returns and the operation costs that form the input for program CROP were developed by the Economics, Water Requirements, and Uses Division of the Texas Water Development Board. In order to compile the data relating the yield potential state of plants in various stages of growth to moisture in the soil reservoir, empirical data coupled with judgment of experienced scientists working in the general areas of soil-water-plant relationships were assembled by the Agricultural Economics Department at Texas Tech University in Lubbock, Texas. The Lubbock precipitation and evaporation gages for the period 1930 to 1965 were used as the historical observations from which the probabilities of specific fluctuations in the soil moisture reservoir were computed.

Government payments were considered in the analysis by assuming that the farmer would not violate



A. Historical rainfall and evaporation

B. Consumptive use coefficients

Soil Moisture Level program computes probabilities of changes in soil reservoir due to precipitation and evaporation

C. Degradation in yield potential due to decreased soil moisture

D. Probabilities of changes in soil moisture state and corresponding transitions in yield state for each crop, month

E. Costs

CRop OPtimization model develops optimal irrigation schedules for individual crops by stochastic dynamic programming

F. Returns

H. Fixed irrigation costs

I. Allotment restrictions

G. Yield state transitions, optimal expected returns, and corresponding decisions

CRoP MIX Program is and LP model to select cropping patterns

K. Planting and harvest months for each crop

INTFC rearranges input data for more efficient use by ECOP

J. Optimal returns and cropping patterns for various levels of soil moisture and surface water

L. Yield state transitions, marginal returns, and corresponding decisions reordered by month

EConomic OPeration subroutine simulates the irrigation system by operating the schedule of water over several regions with several crops

M. Number of acres to be serviced each year in the simulation

P. System response (benefits and costs)

N. Supply model parameters

Simulation Model IV is the surface water supply model

O. Hydrology

Figure 20

Dynamic Economic Simulation of an Irrigation Use and Water Supply System

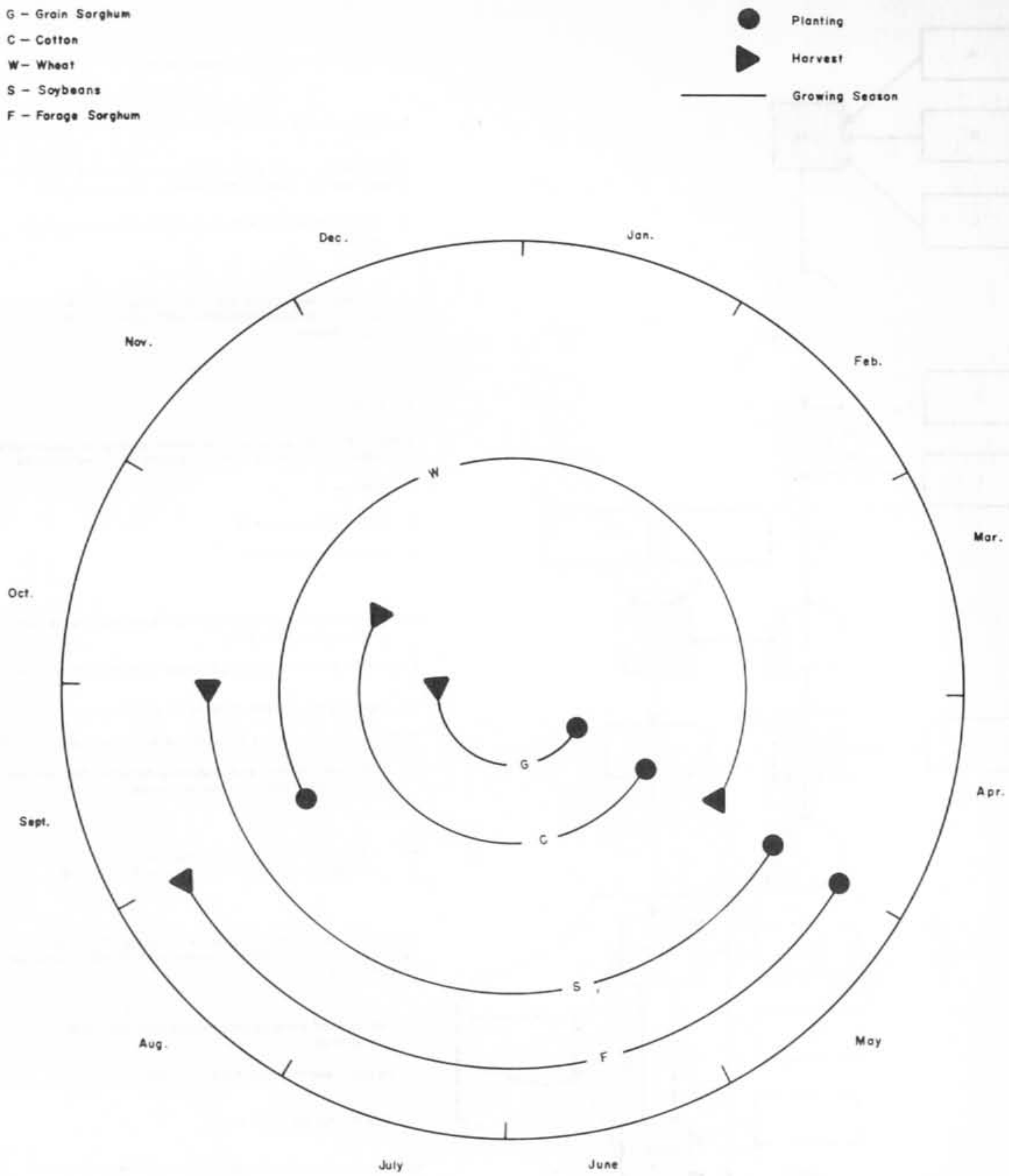


**Figure 21. Length of Growing Seasons for Principal Crops Grown in the Texas High Plains**

any of the allotment restrictions placed upon him by government programs. The constraints in the linear programming model, CRPMX, specify that:

- The total acreage of the three program crops—grain sorghum, cotton, and wheat for grain—may not exceed the acreage available less the specified acreage set aside in each region.
- The total acreage of all the crops must not exceed the acreage to be served by the supply system.
- To preserve "history," or the right to an allotment, at least 45 percent of the cotton allotment must be planted.
- Similarly, at least 45 percent of the grain sorghum allotment and 90 percent of the wheat allotment must be planted in either of these two crops.
- No more than 5 percent of the total acreage may be planted in soybeans in the North High Plains or in forage sorghum in the South High Plains.

- The water used by all activities must not exceed the total quantity available to the farm.

## Analysis of the Irrigation Demand

The irrigation model, subroutine ECOP, receives the estimates of the expected availability of irrigation water from the system simulation model, SIM-IV, and returns to SIM-IV the quantity of water used each month. In most cases the amount of water available to agriculture is the total amount available to the region less the municipal and industrial requirements, which have priority of use.

The impacts of different water supply schedules can be examined by running different time streams of expected water availabilities through the model, holding the acreage constant and using the same hydrologic sequence. Figure 22 illustrates the response of water usage and cash flow to the following three annual supply conditions:

A. An initial estimate of 3 million acre-feet that is realized exactly, with no upward or downward revisions;

B. An estimate of 1 million acre-feet which is revised upward by 1 million acre-feet in July an additional 1 million acre-feet in August; and

C. An initial estimate of 5 million acre-feet which is subsequently reduced by 1 million acre-feet in July and 1 million acre-feet in August.

It is important to note that the total annual water availability for the three sequences listed above is the same, 3 million acre-feet, with only the pattern of the expectations being different.

According to the analysis, sequence 1 results in a profitable growing year with net returns of $57 million and $44 million for the North and South High Plains, respectively, for a total of $101 million. The quantity of water used is 2.7 million of the available 3 million acre-feet. Because of the low initial estimate of the quantity of water for sequence 2, irrigation of grain sorghum is excluded from the South High Plains with the result that use cannot be made of the water that is found to be available later in the growing season. Consequently, less than 2.5 million of the available 3 million acre-feet would be used and final profits of $52 million and $11 million would be realized. These returns which sum to $63 million are far below the $101 million realized in sequence 1. Sequence 3 results in a loss for the South High Plains because of the large investments required to prepare for a year of estimated high irrigation water availability. Of the available 3 million acre-feet of water, almost 2.9 million is used. Notice that the cash flow in the South High Plains reaches a minimum of $72 million which is far lower than for sequence 1 or sequence 2 (Figure 22). When the expected water is not available these cash outlays cannot be recovered and a loss results. The results of this type of analysis agree quite well with what is expected conceptually by Anderson and Maass (1971) as shown in Figure 23. Curve A is the benefit function for exactly delivering the expected supply. Curves $B_1$ and $B_2$ reflect the results of inaccurate forecasts. This figure illustrates the concept that in the long run benefits are maximized by exactly meeting expectations. The example presented in this study supports this theory.

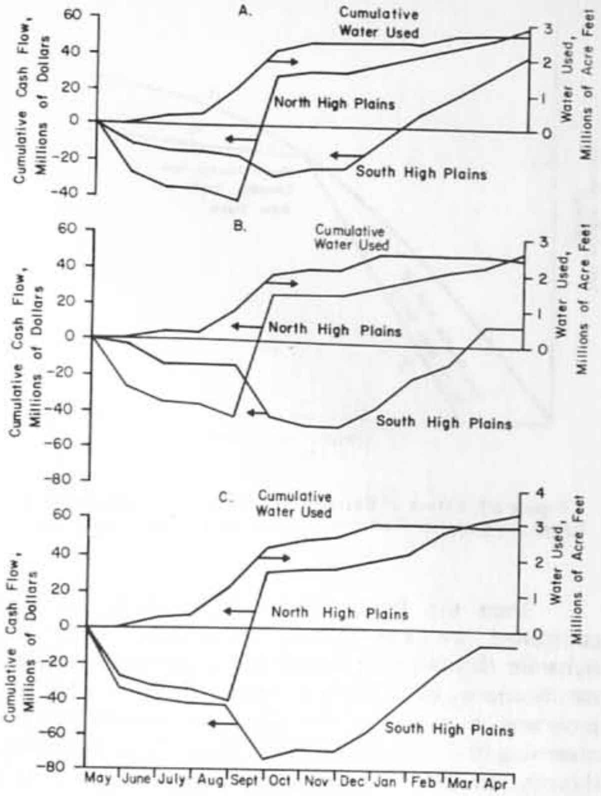


Figure 22. Response of Water Usage and Cash Flow to Various Expected Water Availabilities

The approach developed herein is valuable for examining a broad spectrum of important influences on and output of an irrigation system. Through the use of a Leontief (Leontief, 1951; Grubb, 1970) input-output analysis, the secondary and tertiary effects of such a system can be quantified to estimate the impacts on an entire regional economy, and this approach can be extended to estimate the effects on the whole of society of various water pricing policies. The benefits from increased agricultural production in an area pervade all sectors of the economy and thus provide a justification for state or national funding of construction of such a project.

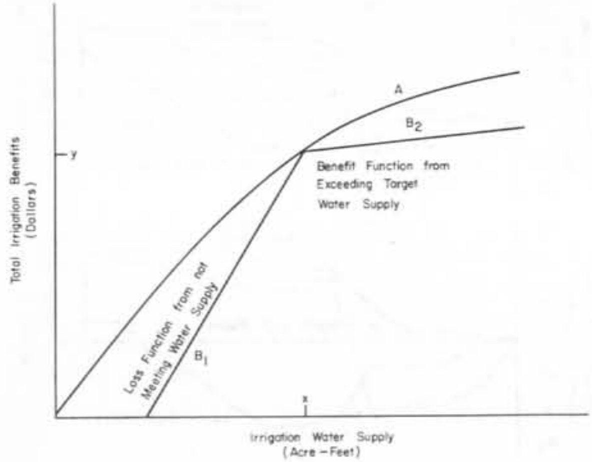
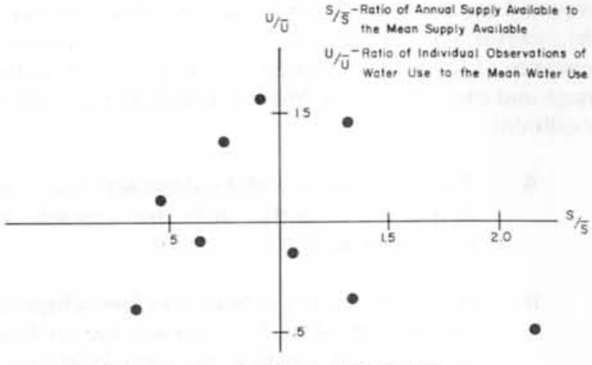


Figure 23. Effect of Expectations of Water Availability on Irrigation Benefits Realized (after Anderson and Maass, 1971)

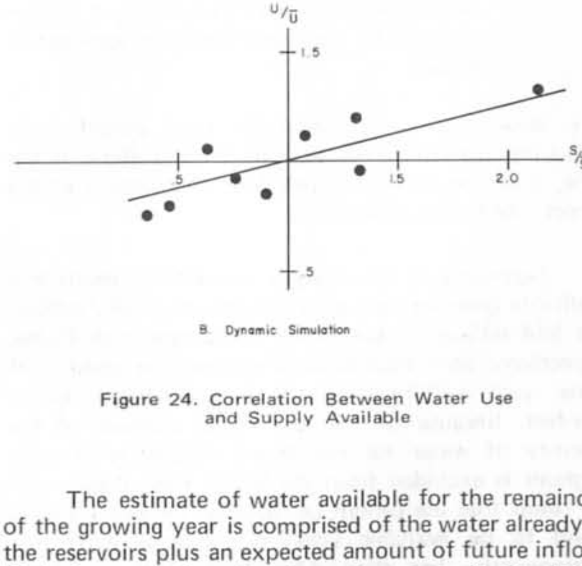
Since the farmers' planting decisions are now controlled by institutional constraints, using this dynamic simulation approach can yield insight into the ramifications of different types of crop allotment programs by varying the allotment constraints and observing the changes in cash flow. Since hydrology directly determines the irrigation supply which in turn determines the productive output of crops, the potential value of weather modification can also by studied with this approach by using enhanced precipitation as a variable in the analysis of supply.

One of the important contributions of this model is that it permits the evaluation of the implications of different policies for allocating water to different regions. Presented in this study is an example where the area allocator distributes water in a manner which maximizes the net returns to the area. However, different circumstances may warrant other policies. For example, if a project is principally financed by one region, the proper allocation policy to follow might be to deliver a firm supply to that region and whatever is left over to other regions. In another instance, where there is no alternative employment for farmers in a region, rather than put them on welfare rolls or cause massive relocation, it might be preferable to support the regional economy by providing water at a price below delivery cost. By adding the allocation of available labor to the multi-resource allocation problem involved in selecting the crop mix at planting time, the effects of different policies on agricultural employment in a region can be analyzed.

It is restated for emphasis that the power of this approach lies in the capability to simultaneously consider many highly variable factors and their interaction. Because this set of models contains and considers many factors it is difficult to compare its output with that of other models. Previous analyses of the Texas High Plains irrigation demand have been done using a simple soil moisture accounting model with the arbitrary policy of filling up the soil moisture reservoir whenever it dropped below 50 percent of capacity (Texas Water Development Board, 1971). No economic interpretations can be made using this method. Since the demand model is run independently of the supply model, there is no correlation between use and supply when individual observations for both are expressed as a ratio to the mean as shown in Figure 24a. However, using the dynamic simulation approach illustrated in Figure 18 results in a system that is responsive to changes in the availability of the supply of irrigation water. This responsiveness is shown in Figure 24b. Since farmers are adaptive in their decision processes, this result is considered realistic.



A. Irrigation Demand and Supply Models Operated Independently (Texas Water Development Board, 1971)



B. Dynamic Simulation

Figure 24. Correlation Between Water Use and Supply Available

The estimate of water available for the remainder of the growing year is comprised of the water already in the reservoirs plus an expected amount of future inflow. If during operation the dynamic economic simulation demands more water than is available at that time, the applications in that month are scaled down by a uniform percentage on all the crops in the area. In the Texas example, this situation occurred in only a few months of the example 35-year simulation sequence.

## Dynamic Analysis of the Demand-Supply System

To analyze the entire water supply-demand interaction, the dynamic economic simulation of the irrigation system has to be performed in conjunction with the detailed water capture and supply simulation models previously described. Computationally, the computer model, SIM-IV, interacts dynamically as discussed on page 105 and shown in Figure 19 with subroutine ECOP which simulates the demand for and use of water. The steps involved in the analysis are those described in Report 131 (Texas Water Development Board, 1971) with provisions made for the inclusion of the dynamic economic simulation into the analysis. In this study, it is assumed that the cost minimization procedure developed in the first two years of research has already been carried out. Specifically, all the data pertaining to the following categories have been collected and refined:

- hydrology in supply and demand area,
- potentially developable reservoir sites,
- cost-capacity information,
- pumping cost information, and
- municipal and industrial demand information.

To develop the data base for the dynamic simulation system depicted in Figure 24, the following types of information are necessary:

- data describing the soil moisture-stress-yield relationships in each of the crops under consideration,
- consumptive use information for each of the crops being considered,
- cost of cultural operations performed on each crop and the effects of irrigation on these costs, and
- planting restrictions on acreage of the various crops.

Much of the preliminary analysis using this simulation approach is considerably enhanced through the insight gained with the cost minimization procedure. A great many inferior arrangements of facilities to pump water from East to West Texas have already been discarded in the plan development and plan improvement steps in the previous analyses. Moreover, a great familiarity with the response of the entire system to changes in such factors as canal sizes and reservoir sizes and timing has been gained by the analyst. Just as important, the effects on the system of various sets of operating rules have already been examined. Because of this insight it is desirable to start with the optimum p
developed by the previous analysis and to try to impr
upon it. Since the labor involved in the analysi
directly dependent upon the goodness of the start
point, this is a desirable point of departure. The quest
again arises, what is the criterion for evaluating
goodness of a plan?

Often the stated goal of planning is to maxim
the net benefits to society from the plan formulat
However, cost minimization alone does not guaran
that maximum benefits are achieved. The next questi
that arises is, what is to be considered and how are t
factors considered valued in the assessment of benefi
Obviously, there are immediate benefits to the actu
users of the water supplied. These are termed prima
benefits. Additionally, there are positive as well
negative secondary economic and environmental impa
that pervade the entire economy. There are ma
benefits and costs, such as the social and aesthe
effects, that defy quantification. Following t
philosophy presented earlier, a good framework f
initial analysis might be the maximization of primary n
benefits to agriculture in the High Plains. Just as in th
previous approach, the effects on factors that are n
economically quantifiable, such as quality of life, can b
evaluated after the optimization has been performe
using a more narrow criterion. Since the benefi
resulting from supply of municipal and industrial wat
are difficult to assess, the previously introduce
convention of penalty costs is used to drive the syste
to meet these demands. The high penalty cost is justifie
on the basis that the benefits from delivering water t
municipal and industrial users are usually higher tha
those from delivering the same amount of water t
irrigation users, and thus, these former uses take firs
priority in times of shortage.

Using the plan developed in the previous analysi
as a starting point, the problem becomes one of sizin
the capacity of the mainstem canal to maximize primar
net benefits. In the general case, restricting the size o
the irrigation service area must also be considered. Fo
the assumptions of 2020 conditions and a price charge
to the farmer of $12.00 per acre-foot for water, the ne
benefits calculations for varying capacities of the
mainstem canal are shown in Table 7. Each entry
represents the results of the analysis of a 36-year
simulation period using DES. To obtain a measure of the
benefits from irrigation, the dryland alternative of
$0.809 billion is subtracted from the first column of
benefits. This primary benefit to dryland production is a preliminary estimate by the Economics, Water Requirements, and Uses Division of the Texas Water Development Board. As shown in Figure 25, the benefits from irrigation increase as the capacity of the mainstem canal is increased, reflecting an increasing ability to transfer water to meet all possible demands. However, this curve flattens at approximately 8,000 cfs implying that additional increases do not result in higher total returns to the irrigators. The water usage in this example

### Table 7.—Dynamic Economic Simulation Analysis of the Example Problem, Trans-Texas Division of the Proposed Texas Water System

| Mainstem Canal Capacity (cfs) | Primary Benefits (Billions of dollars) | Dryland Reture (Billions of dollars) | Benefits To Irrigation[1] (Billions of dollars) | Demands Met (Millions of Acre-Feet) | Annual System Costs (Billions of dollars) | Net Costs[2,3] (Billions of dollars) | Net Primary Benefits[4] (Billions of dollars) |
|---|---|---|---|---|---|---|---|
| 3,000 | 0.987 | 0.809 | 0.178 | 0.0705 | 2.73 | 1.88 | -1.70 |
| 5,000 | 2.17 | .809 | 1.36 | .0964 | 3.51 | 2.35 | - .99 |
| 7,500 | 2.81 | .809 | 2.00 | .103 | 4.08 | 2.84 | - .84 |
| 15,000 | 2.89 | .809 | 2.08 | .165 | 5.15 | 3.89 | -1.81 |

[1] Benefits to irrigation equals primary benefits minus dryland return.
[2] Net cost equals system cost minus price paid by farmers multiplied by the demands met.
[3] The price paid by farmers for water is $12.00 per acre-foot.
[4] Net primary benefits equals benefits to irrigation minus net cost.

is lower than in the previous analysis primarily because of the use of the assumption of rational irrigation rather than using an arbitrary demand for water that occurs whenever the soil moisture drops below 50 percent of capacity. Because there is a charge for water, the dynamic economic simulation approach uses it more sparingly. The system costs can be expected to increase directly with the capacity of the mainstem canal due to the large capital costs associated with canal construction and the power costs associated with pumping. However, as shown in Table 7, the net cost is somewhat reduced by the cash return generated by charging the assumed price of $12.00 per acre-foot for the water delivered to the farmer. The net benefits in the context of this analysis are the benefits from irrigation less the net costs incurred.

Referring to Figure 14, the effect of increasing the price paid by the farmer to above $12.00 per acre-foot is readily seen. The expected net return per acre of crop drops drastically with increasing water price and the amount of water used at the higher prices rapidly decreases. Thus, the primary net benefits from irrigation can be expected to drop with increasing cost of water to the farmer.

As shown in Figure 25, the net benefits are maximized at a mainstem canal capacity of 6,500 cfs. It is important to notice that the curve of net primary benefits never becomes positive. This implies that if the only justification for building the project were the increase in primary benefits to the agricultural users of the water, it would be best not to construct the project at all. However, since there are beneficial uses of water by municipal and industrial users as well as secondary impacts on the economy from agriculture, it is possible that these more than compensate for the $0.8 billion deficit. Considerably more economic analysis is required to determine the efficacy of a water resource system of this magnitude. Such an analysis is beyond the scope of this investigation.

Assuming that the net benefits are positive, the question remains of who is to pay for the system cost above what the farmer pays for the water he uses. It is not be object of this study to determine tax basis or ability to pay by society in general. However, it is important to point out that this is a problem that has to be recognized by the planner.

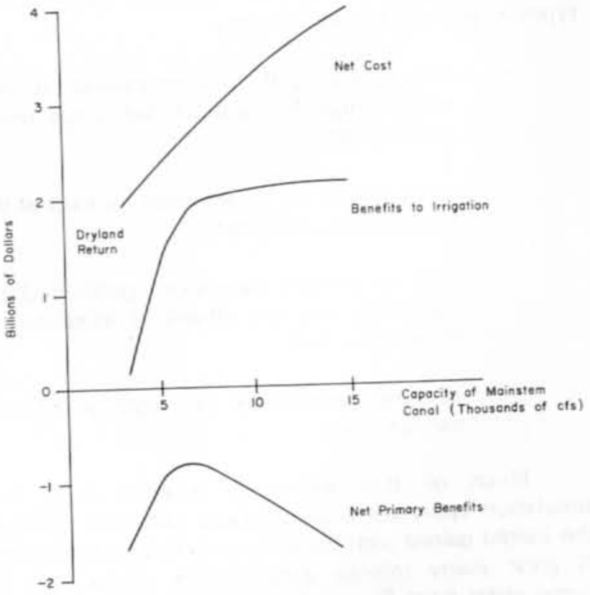


Figure 25. Dynamic Economic Simulation Analysis of the Example Problem—Texas High Plains

# V. SYSTEM WATER QUALITY SIMULATION

In the previous research, water quality was not directly considered in the analytical techniques developed for optimizing the system. Obviously, it is not sufficient to merely supply a given quantity of water; the water supplied at every demand point in the multibasin water resource network must be of a suitable quality, or at least treatable to a quality suitable for all intended uses. In developing a comprehensive and intelligent plan for the development of a large-scale water resource system, a means of quantifying its effects on water quality is necessary.

An initial step in considering water quality in the system simulation and optimization process is the development of a technique to route "conservative" water quality constituents through a water resource network. By definition, the "conservative" water quality constituents are unaffected by chemical and biological processes, but are subject to dilution by better quality water or concentration by evaporation. Typically, chloride, sulfate, and total dissolved solid concentrations are considered to be conservative in nature in most fresh water systems. These constituents are important in determining the suitability of water for municipal, industrial, and agricultural uses and are discussed in detail in *Water Quality Criteria* (U.S. Federal Water Pollution Control Administration, 1968).

In order to identify and analyze the various alternatives of interbasin transfer and their impact on the conservative water quality at each demand point, QNET-I* was developed to utilize the analytical results from the quantitative simulation model, SIMYLD-II,* to analyze the water quality at every location (demand point, reservoir, and connecting link) in the minimum-expected cost water resource system for each month during the simulation period. At the present time, it is not computationally feasible to directly include water quality criteria as constraints in the optimization technique used in the simulation models. However, the water resources planner can use the output of the water quality assessment model to assist in evaluation of the network analysis performed by the simulation and optimization models. It can thus be determined whether or not the "quantitative optimal" network developed to meet a specified set of demands is acceptable with respect to the quality of the water delivered at each demand point. Thus, the concentrations of conservative water quality constituents at the demand points in an interbasin transfer system can be considered, indirectly, as a constraint on the optimization process used to develop a network and allocate water to meet specified requirements.

The QNET-I model is quite flexible and can be adapted to any network of reservoirs, canal junctions, and connecting links. One major restriction is that the effects of thermal stratification which occur in large, deep impoundments cannot be considered by this model since complete and immediate mixing is assumed at all nodes. In most cases involving conservative water quality constituents, the effects on the simulation caused by neglecting this phenomenon are negligible. The output from a single run of the QNET-I simulation model can provide the user with a complete description of the spatial and temporal levels of the selected water quality constituent within the network investigated.

## Analytical Approach

Mass balances, over both space and time, form the fundamental set of equations that must be solved in the network water quality model, QNET-I. The basic equation is simply a statement of the conservation of mass and may be written as:

$$\frac{\Delta\ \text{Mass}}{\Delta\ t} = \Sigma\ \text{mass inflows}_{\Delta t} - \Sigma\ \text{mass outflows}_{\Delta t}$$

The mass of a particular water quality constituent is related to its concentration by:

$$\text{Concentration} = \frac{\text{Mass}}{\text{Volume}}$$

The water quality analysis is done by QNET-I on a mass basis, with the masses of constituents being converted to a concentration basis prior to presentation of the analytical results. The terms in the mass balance equation for a typical storage element (reservoir), as shown in Figure 26, used in the simulation analyses can be represented by the following expression:

$$\begin{array}{l} \text{The rate of change of mass in storage} = \left[\text{mass in upstream releases} + \text{mass in pumped inflows} \right. \\ \qquad \left. + \text{mass in unregulated inflows} + \text{mass in imports}\right] \\ \qquad - \left[\text{mass in controlled releases and spills} + \text{mass in pumped outflows} \right. \\ \qquad \left. + \text{mass in local demands}\right] \end{array}$$

It should be noted that the net evaporation term is not shown in the mass balance equation. This is because

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* The QNET-I and SIMYLD-II models are described in detail in the program documentation volumes of this Completion Report

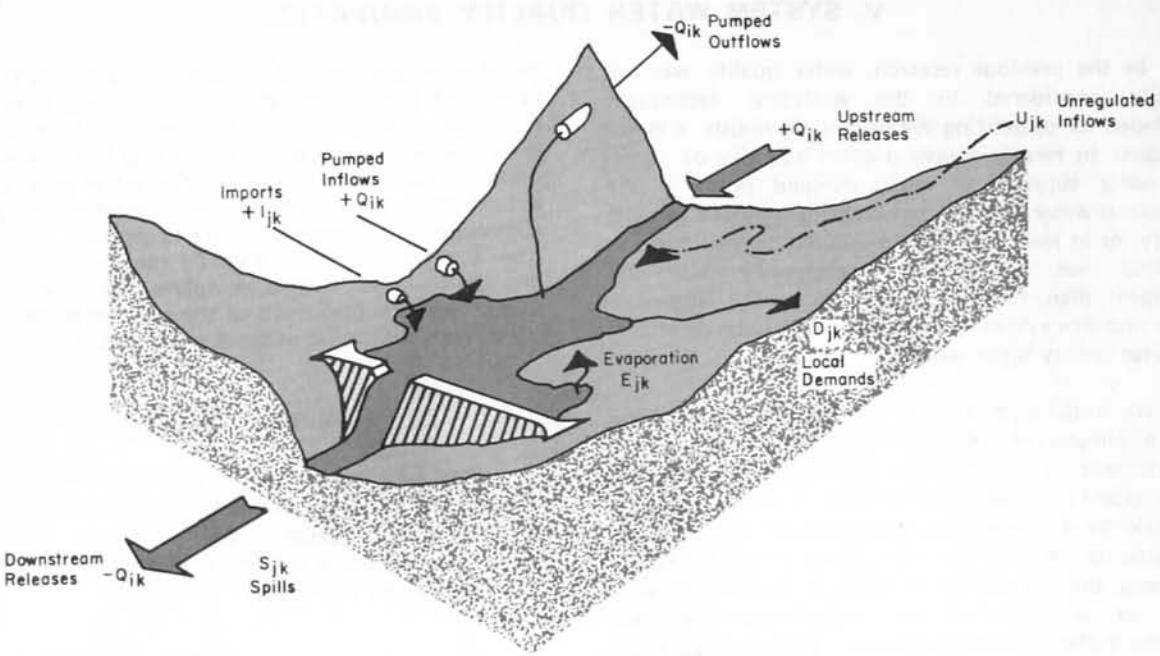


**Figure 26. Basic Terms in a Mass Balance for a Reservoir**

net evaporation (precipitation or evaporation) does not add mass to the system since atmospheric water is considered to have essentially zero concentration of conservative mineral constituents. The evaporation effects are taken into account by adjusting the initial and final reservoir contents at each time step before solving the equation.

In addition to reservoirs, which constitute storage nodes in the simulation model, there are two types of nodes which do not permit storage of water. These are canal and/or stream junctions and demand points on canals or streams. At the non-storage nodes, changes in storage, evaporation, unregulated inflows, and spills are not permitted.

An important step in the use of QNET-I is the definition of the quality of the unregulated inflows to each reservoir and of water imported into the system. There are two available techniques for providing this input to the simulation model. These methods are:

> Use as program input a sequence of water quality data that corresponds to a specific hydrologic sequence at a given inflow location. This is the desirable method if, for example, a complete sequence of historical water quality data are available.
>
> Alternately, the model can accept the coefficients of an equation describing the discharge-quality relationship for a given inflow and then use the hydrologic sequence at that node to generate the corresponding water quality. Several mathematical formulations can be used by this model to define the quality-discharge relationship.

Both of these formulations also include a technique that introduces a random component to the water quality data to preserve the variance inherent in the discharge-water quality relationships.

As previously discussed, QNET-I is designed to operate conjunctively with the quantitative simulation model SIMYLD-II. SYMLYD-II is based on a network representation of a water resource system where the optimum or least costly means of transferring water to points of demand is determined on a monthly basis. The resulting output from SIMYLD-II contains the unregulated inflow for each node, the beginning and ending monthly storage at each node, the volume of water transferred in each link (both river reaches and pump-canals) of the system, and the volume of water diverted from each node to supply system demands for each month in the simulation period. This information is used directly by QNET-I and forms the basis for the mass balance performed for the conservative constituents.

The water quality simulation provides the planner with a tabular listing of the concentration of each water quality constituent in every reservoir and at every demand point in the system for each month of the simulation period. This type of information can be statistically analyzed and graphically displayed as shown in Figure 27 to assist the planner in the evaluation process. For example, the recommended maximum chloride concentration for drinking water is 250 mg/l; water of poorer quality may be undesirable for the satisfaction of municipal demands. Similar limits exist for a variety of water quality constituents for many types of uses, municipal, industrial, and agricultural. The system simulation can provide the planner with the necessary information to determine which, if any, water quality criteria are not met. If the limits are desirable or preferred limits rather than absolute (health standards), then the frequency of exceedence of limits for each important constituent enters into the planning process. The extra costs incurred to modify a system to provide better quality water could be balanced against the benefits derived from the improved supply. Obviously, if an established water quality criterion is exceeded only several months in a 50-year simulation sequence, the benefits foregone are much less than if the criterion is exceeded 50 percent of the time. Certain of these water quality benefits can be described in terms of market values. Some of the effects of increasing concentrations of the hardness-causing agents (principally calcium and magnesium), for example, are inversely correlated with the usable lifetime of various water system components (e.g., home water heaters, distribution system components, etc.). An example of this type of effect is shown in Figure 28. These effects can be put in monetary terms by estimating the replacement rate and cost for the principal water system components. Similar analyses can be made for other significant water quality constituents for each type of demand (municipal, industrial, and agricultural). The results of the water quality simulations and the supporting analyses give the water resource planner additional important information to assist in the selection of viable alternative plans.

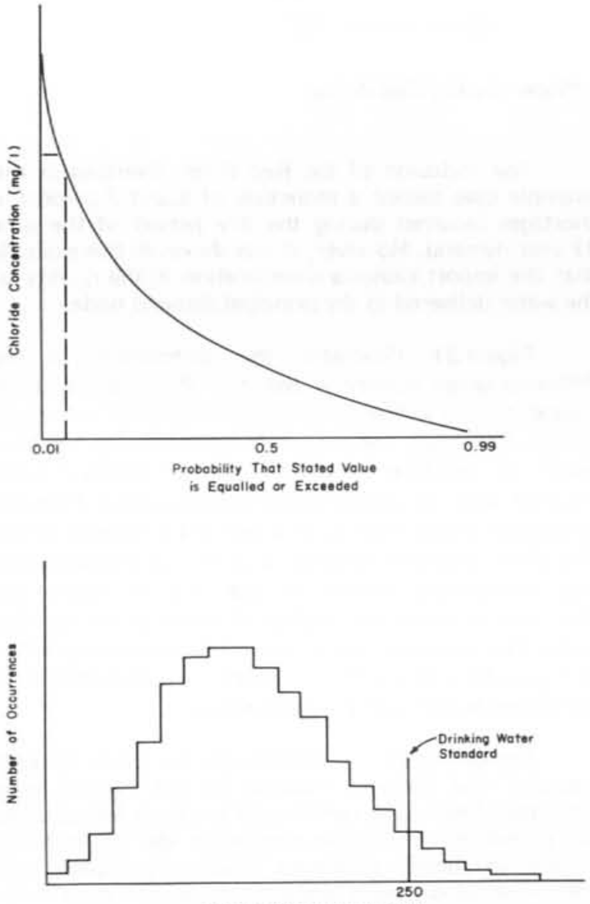


Figure 27. Typical Analysis of Simulated Water Quality at a Demand Location

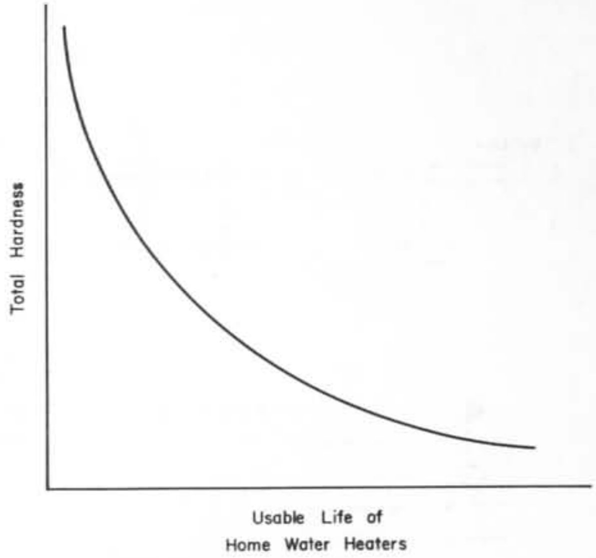


Figure 28. Typical Water Quality Effect on a Municipal Water System Component

## Example Analysis - The Texas Water System

In order to demonstrate the application of the water quality simulation technique, two simulations were performed using the Trans-Texas Division of the Texas Water System as an example case. The configuration used for this problem is composed of 12 nodal reservoirs, a total of 17 demand points, and 35 potential transfer canals and river reaches arranged spatially as shown in Figure 29.

The largest water demand on the system occurs at node 17 which represents the large irrigation requirements in West Texas. The projected average annual irrigation demand on the High Plains for the year 2020 is 6.6 million acre-feet and this figure was used for the example simulation.

Historical hydrology for the period 1941 through 1957 was used for this example. This sequence of events contains one of the wettest cycles of record (1945-1946) as well as one of the worst droughts (1955-1957) on record. It should be pointed out, however, that the average annual supply during this 17-year period is approximately 15 percent higher than the 40-year average; therefore, the results obtained would appear to be optimistic with respect to available supplies.

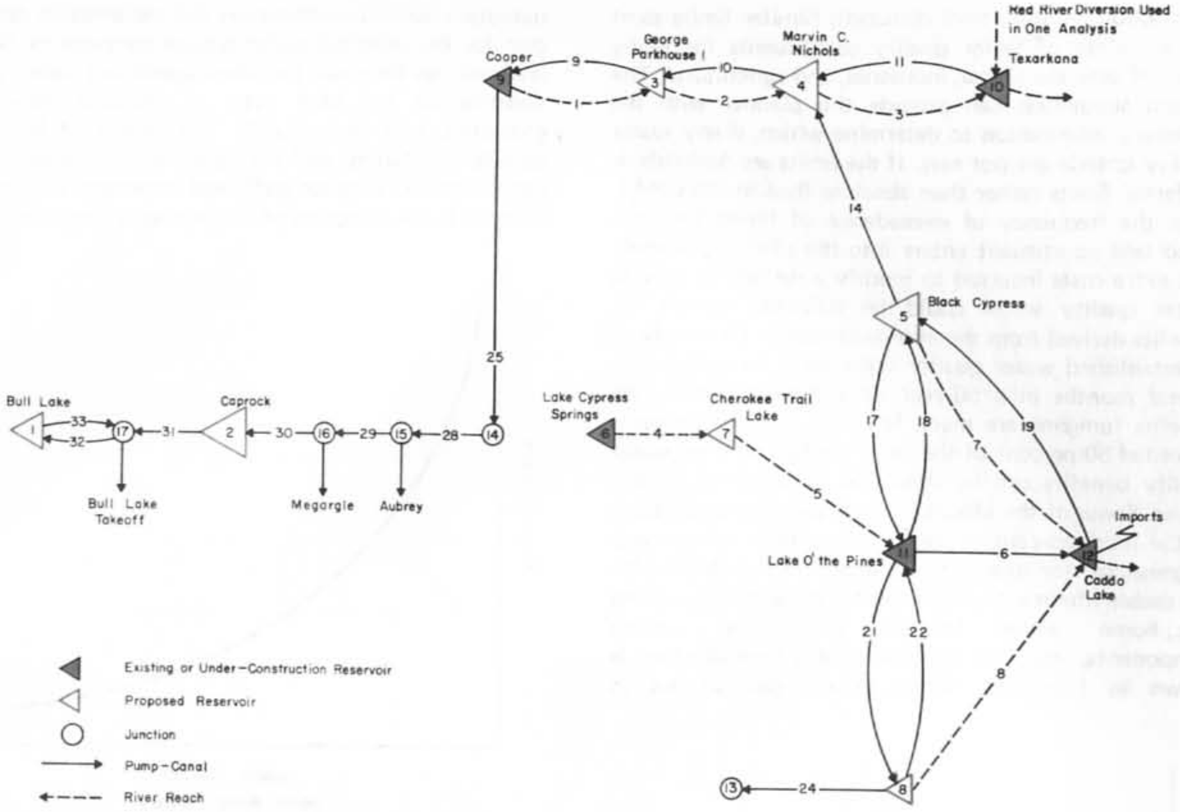


Figure 29. Example System Used in Water Quality Simulation

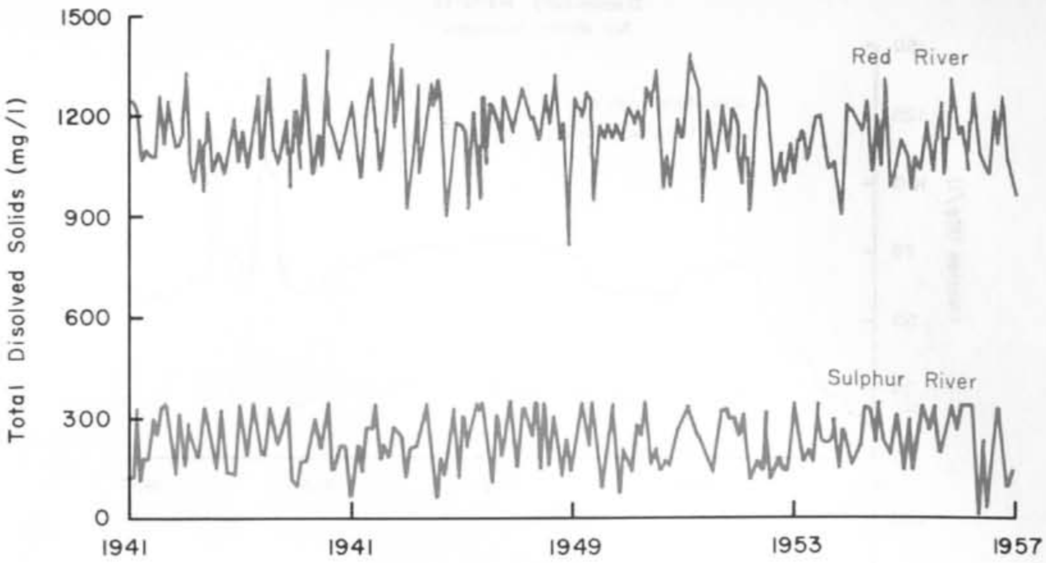
Two separate analyses were selected for demonstration of the QNET-I model. These simulations were based on the system configuration shown in Figure 29 with a total intrastate storage of approximately 14 million acre-feet. The difference between the two analyses is the inclusion of an interbasin diversion from the Red River in the second analysis.

The water quality of the Red River is significantly poorer than that of the East Texas rivers and the Mississippi River import. For example, at a flow rate of 100,000 acre-feet per month, the expected total dissolved solids concentration in the Red River is approximately six times the concentration of total dissolved solids in either the Sulphur River or Cypress Creek basins into which it would be transferred. This relationship is shown in Figure 30. Although the volume of Red River water transferred into the system is not large when compared with the other supply sources, the effects of the Red River water become critical during the drought periods. The average annual volume of water transferred from the Red River basin is approximately 700,000 acre-feet compared to a total supply in the Sulphur and Cypress basins of over 4 million acre-feet. This interbasin diversion enters the system in the Sulphur basin and represents about 25 percent of the average annual supply of that basin.

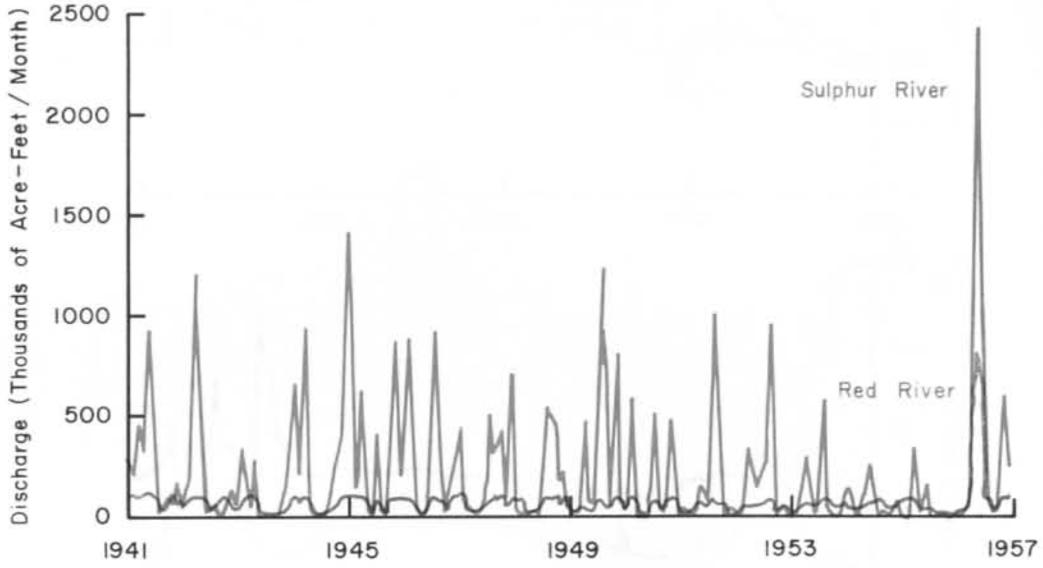
The inclusion of the Red River diversion in this example case caused a reduction of about 2 percent in shortages incurred during the dry period of the total 17-year demand. However, it was shown in this example that the import causes a deterioration in the quality of the water delivered to the principal demand node.

Figure 31 illustrates the differences in the delivered water quality at the High Plains demand site caused by the inclusion of the Red River as an import source. The sharp rise in concentrations during 1954 is a result of low-flow conditions in the Sulphur basin coupled with no import water being available from the Mississippi River. During this period the volume of the Red River diversion becomes large relative to the storage and unregulated inflow in the Sulphur basin and therefore degrades the quality of water at the terminal node. The periods of zero concentration (discontinuities in Figure 31) indicate that no water was available to meet the demands during the months shown.

Similar types of analyses can be made for each reservoir and demand location in the system being simulated. The results can be used as a basis for adjusting the operating rules in the simulation and optimization models to specify minimum flows or pumpage from areas with good quality water to those with poor water quality. This allows the inclusion, as a constraint, of a variable that cannot be explicitly considered in an objective function.



TDS Concentrations for the Sulphur River and the Red River Diversion



Unregulated Inflow for the Sulphur River and the Red River Diversion

Figure 30
Quantitative and Qualitative Comparison of the Sulphur River and Red River

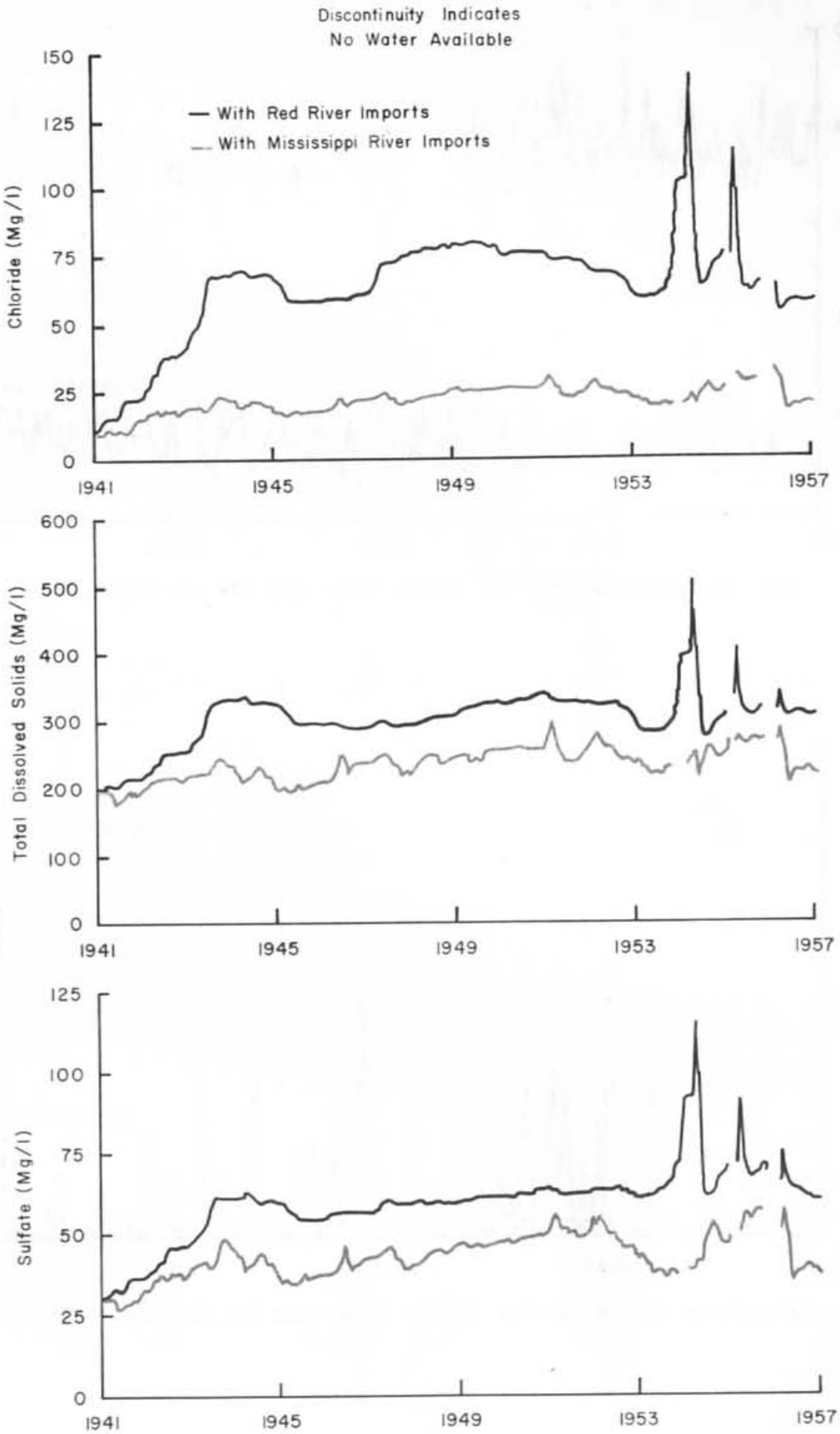


Figure 31
Predicted Water Quality at High Plains Delivery Point
(Bull Lake Takeoff)

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