TEXAS WATER DEVELOPMENT BOARD

REPORT 183

ANALYTICAL TECHNIQUES FOR PLANNING COMPLEX WATER RESOURCE SYSTEMS

A Summary Report

The work upon which this publication is based was supported in part by funds provided by the Office of Water Resources Research, United States Department of the Interior, as authorized under the Water Resources Research Act of 1964 as amended.

April 1974

Published and distributed
by the
Texas Water Development Board
Post Office Box 13087
Austin, Texas 78711

FOREWARD

The Texas Water Development Board began a long-range program of applied research in 1967 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 now completed the last phase of a three-phase program. This volume summarizes the results of this three-phase effort, the primary objective of which was to develop a practical methodology and attendant models for evaluating the impact that stochastic variability of both the supply and demand for water has on planning for the optimal development of a complex water resource system.

This report has been prepared for widespread dissemination for the purposes 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

This report describes the research experience of a state-level water planning and development agency over the period 1965-1972. The Texas Water Development Board, constitutional water planning and development agency for the State of Texas, in this period initiated and conducted a sustained program of research that has developed techniques useful in decision-making believed to be generally applicable to water planning problems elsewhere.

The Board confronted a complex planning problem in 1965. The limited water resources available to the State, and the diverse, sometimes competitive, projected demands on those resources appeared to place unacceptable limits upon the achievement of the State's economic, social, and environmental goals. Then Governor John Connally and the Texas Legislature, concerned with this resource problem, determined that achievement of the State's goals would require a long-range water plan, that could be implemented in stages over a 50-year span—or longer—retaining options for adjustment of the plan to meet changing conditions. The Board was directed to develop such a plan. The preliminary water planning effort undertaken by the Board was conventional in nature, and relied largely upon traditional analytical and planning techniques. This preliminary effort clearly demonstrated that planning to solve current and future water problems required new techniques of analysis and decision-making that would not have been possible, except in a conceptual sense, before high speed large-capacity computers were available. With these computational tools and the corollary development of systems analysis techniques, planning entered a new dimension. In the case of the Texas situation, it appeared that public investments in water development could be planned and implemented in stages, and that decisions could be guided by the experience of actual project development and funding commitment while a wide range of alternatives were examined and considered for adjusting the framework Texas Water Plan to changing future conditions of water supply and demand.

The preliminary Texas Water Plan was formulated without the aid of systems analysis techniques. System simulation techniques were developed to assist in solving some of the long-range water planning problems identified in formulating the preliminary Plan and in formulating and refining the Texas Water Plan.

Throughout the research effort, the Board has been supported by the cooperation and financial aid of the Office of Water Resources Research (OWRR) in the United States Department of the Interior.

In this report, the conditions dictating the constraints and opportunities of the Texas Water Plan are described, the sequential steps in the research program and its results are outlined, and proposed facilities of the Texas Water System, major physical works component of the Plan, are used as an example for research and development of new planning techniques.

Description of the Report

This report discusses a set of analytical techniques which were developed to assist the planning of water resources projects. The research which resulted in these techniques was initiated because of the water resources problems of the State of Texas. Chapter I describes the Texas water situation and thus provides the setting for the development of the planning techniques to be discussed.

Chapters II and III discuss the Texas Water Plan and its formulation using traditional planning techniques. The complexity of the Plan and the need for more detailed evaluations emphasizes the need for sophisticated and faster analytical tools. The Water Plan serves as the basis for the Board's continuing planning activities and the great number of alternatives listed therein must be carefully evaluated. The models developed by and for the Board are designed for this purpose.

Chapter IV discusses the function and uses of these analytical techniques in the water resources planning process. In this chapter the interaction between planning and systems analysis is discussed, and a planning methodology using these tools is presented.

Chapter V presents the heart of the research effort to date, the analytical models designed to simulate water resources systems. This chapter includes descriptions of all of the models and analytical techniques developed by the Board, both with partial funding from the Office of Water Resources Research and with State funds exclusively. Included with each model description is a discussion of actual applications of the models to Texas water resources problems. The models and techniques presented cover a wide variety of water resources systems: surface water supply systems, surface water hydrology, ground water, estuarine hydrodynamics and mass transport, stream water quality, and agricultural water demands.

Chapter VI presents an example, using the Texas Water System as a test case, of the planning application of the surface water system simulation-optimization models which have been developed by the Board. This example is designed to illustrate to the reader the additonal information which systems analysis techniques provide the planner. Although this example does not show the use of the ground-water and environmental models, the reader should recognize the potential information which can also be made available to the water resource planner.

Acknowledgements

A great many individuals have shared in the development and application of the techniques described herein. Thanks are due all of these people and, unfortunately, space does not permit individually acknowledging all those involved in the work presented in this report.

The major amount of model development described herein was accomplished by the staffs of the Systems Engineering Division of the Texas Water Development Board; Water Resources Engineers, Inc.; and Frank D. Masch and Associates. The work at the Board was accomplished under the overall project direction of Lewis B. Seward, Principal Engineer - Project Development. Dr. Gerald T. Orlob and Dr. Frank D. Masch had overall responsibility for the work accomplished by Water Resources Engineers, Inc., and Frank D. Masch and Associates, respectively.

Assistance in all phases of the Office of Water Resources Research funded research was provided by the Consulting Panel which consisted of Dean Dean F. Peterson, Chairman; Harvey O. Banks; Leo R. Beard; Dr. Ven Te Chow; Dr. Herbert W. Grubb; and, for a short while, Dr. Allen V. Kneese. Throughout all three OWRR projects described herein they reviewed progress and provided guidance to the research staff.

The research staff wishes to acknowledge the support given the projects by the Texas Water Development Board, its members individually, and Harry P. Burleigh, Executive Director.

The advice and encouragement given by the Office of Water Resources Research staff are greatly appreciated. In particular, the decision to partially fund a state water resources agency in its effort to apply the techniques of systems analysis to water planning represents a unique and appreciated application of research funds.

To these individuals, and the many who could not be individually acknowledged but without whom none of this work would have been accomplished, the Board research staff expresses their sincere appreciation.

This summary report was compiled and written by Dr. Lial F. Tischler, Director of the Systems Engineering Division; Mrs. Jean O. Williams, Program Controller, both of the Texas Water Development Board; and Dr. Herbert W. Grubb of the Texas Governor's Office of Information Services.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd.)

TABLE OF CONTENTS (Cont'd.)

TABLES

FIGURES

TABLE OF CONTENTS (Cont'd.)

Page

ANALYTICAL TECHNIQUES PLANNING FOR COMPLEX WATER RESOURCE SYSTEMS

A SUMMARY REPORT

I. THE TEXAS SITUATION

Physical Environment

The physical environment of Texas is marked by a wide range of climatic, topographic, and hydrologic conditions. This diversity has influenced the distribution and well-being of the State's people over time. The multiple effects of this diversity must be recognized as significant factors in water as well as other resource planning and development activity.

Climate

Frequent floods, tornados, occasional hurricanes, and recurring severe droughts combine to make climate and weather compelling considerations in Texas water planning and development. An average of approximately 413 million acre-feet of water falls in the State each year as rain and snow, but is poorly distributed both in space and time. Average annual precipitation at Lubbock in the High Plains is about 18 inches, while it is slightly in excess of 49 inches at Texarkana in East Texas. The widest range in average annual precipitation rates in Texas is between 8 inches at El Paso and 55 inches at Port Arthur. Figure 1 and Table 1 show the major climatological divisions in the State and the average annual precipitation for each division.

There were 11 major droughts in Texas between 1889 and 1960. Of particular significance to water planning is the fact that the severe drought conditions do not occur simultaneously throughout the State, but overlap progressively in time and space, generally from west to east. The drought between 1954 and 1956 combined with the less severe drought conditions from 1950 to 1954 to produce the most intense 7-year statewide drought period that has been experienced within the 70-year period of hydrologic record.

Topography

Texas is part of four major physiographic provinces of North America—the Gulf Coastal Plain, the Great Plains, the Central Lowlands, and the Basin and Range province. Aside from weather, the variation in this largely plains environment is the principal factor controlling surface water resource occurrence in Texas.

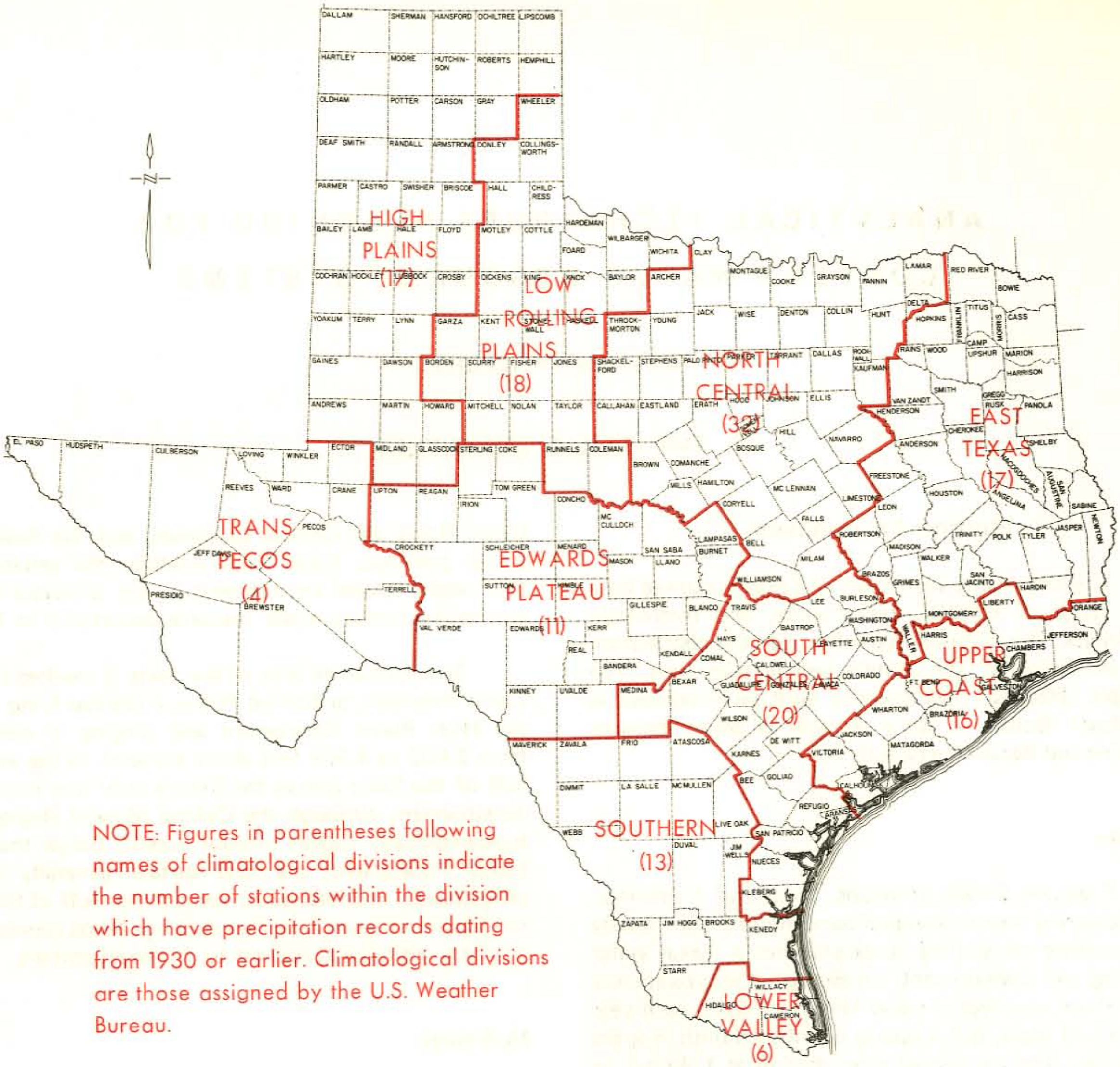
The Panhandle area of the State is marked by the Llano Estacado, or Staked Plains, a plateau lying above the High Plains Escarpment and ranging in elevation from 2,600 to 4,300 feet above sea level. In the western half of the State occurs the State's only true mountain development, although the Central Mineral Region is a topographically rugged interior accent. Below the High Plains Escarpment, the land surface generally slopes progressively southeastward toward the Gulf of Mexico. As shown in Figure 2, surface drainage tends generally to conform with this northwest to southeast pattern.

Hydrology

Streamflow in Texas varies within wide ranges as does the precipitation rate (Figure 3). Average annual runoff is 39 million acre-feet, decreasing from about 1,100 acre-feet per square mile at the eastern boundary of the State to practically zero in large areas of extreme West Texas. Approximately three-fourths of the total runoff occurs in the eastern one-fourth of the State. Approximately 10 percent of the total runoff in the State is from coastal areas where capture and use of the water is difficult because reservoir sites are either unavailable or economically infeasible.

Runoff varies sharply not only as a function of geography but of time. The average annual runoff between 1940 and 1946 was about 59 million acre-feet, while during the drought between 1950 and 1956 the average was about 24 million acre-feet. There is also considerable intra-seasonal variability of precipitation and runoff within regions of the State.

Traditional development of surface water has taken place during the past 50 years through construction of more than 100 major storage reservoirs and thousands of small reservoirs and farm ponds.



NOTE: Figures in parentheses following names of climatological divisions indicate the number of stations within the division which have precipitation records dating from 1930 or earlier. Climatological divisions are those assigned by the U.S. Weather Bureau.

Figure 1.—Texas Climatological Divisions

Ground water, a principal water resource in Texas, supplying approximately 75 percent of the water consumed in the State, is found in geographically widespread underground water-bearing formations (aquifers). These aquifers are not uniformly distributed through the State although they underlie approximately 65 percent of the State's land surface.

Ground water is produced from seven major aquifers in the State, and from many minor aquifers of local importance. Major aquifers are the Ogallala, Alluvium, Trinity Group, Carrizo-Wilcox, Gulf Coast, Edwards-Trinity (Plateau), and the Edwards (Balcones Fault Zone). These aquifers are displayed in Figure 4. Use of ground water for municipal, industrial, and irrigation purposes has grown from more than 670,000 acre-feet annually in 1935, the first year for which records are available, to more than 10 million acre-feet in 1969. Irrigation development was the principal factor in this increase.

Water Availability Problems

Water quality problems, both natural and man-made, are found in much of the State's surface water. The upper reaches of the Red, Colorado, Brazos, and Pecos River basins have base flows of naturally highly mineralized water. Low flows in the Trinity River, coupled with the large volumes of wastes discharged from the Dallas-Fort Worth metropolitan complex in the upper basin, result in water quality problems through much of the river's extent. In the San Antonio River basin similarly are found low-flow conditions combined with a large municipal waste discharge in the upper part of the basin. Local problems associated with present or past waste discharges affect other basins.

A major concern to the State is the effect of upstream development on fresh water inflows to the

Table 1.—Average Annual Precipitation in Texas by Climatological Division

CLIMATOLOGICAL DIVISION	AVERAGE ANNUAL PRECIPITATION[1] (INCHES)
High Plains	18.51
Low Rolling Plains	22.99
North Central	32.93
East Texas	45.96
Trans-Pecos	12.03
Edwards Plateau	25.91
South Central	33.24
Upper Coast	46.19
Southern	22.33
Lower Valley	24.27

[1] From "Decennial Census of United States Climate, 1931-1960," U.S. Weather Bureau, 1963.

Gulf bays and estuaries. Use of the bays for navigation, commercial shell dredging, commercial and sport fisheries, oil and gas production, maintenance and propagation of marine life, and diverse recreational use is extensive. These activities make a major contribution to the viability of the State's economy. The effects of these activities on the biology of the bays, their hydrology, quality, and temperature conditions, and the stresses imposed by varying conditions on the estuarial ecosystem, have not been fully described, measured, and quantified.

Serious flooding conditions have at one time or another struck most parts of the State. Flash flooding, resulting from characteristic high-intensity rainstorms, is common and not easily predicted or controlled. Also, the flat coastal plain is vulnerable both to high tides and to heavy runoff from rainfall associated with tropical storms. In the coastal plain, and in some other parts of the State, the flat land surface is not particularly amenable to runoff control by structural measures.

Evaporation is a major concern in water resource development planning, especially in the more arid portions of West Texas. While rainfall largely offsets evaporation losses in East Texas, it does not do so in the west. In the period 1940 to 1970, the average annual net lake surface evaporation rate was between 0 and 20 inches along the eastern edge of the State and more than 80 inches in the Big Bend in West Texas.

Extensive development of ground water has resulted in numerous problems, some local in nature, others more widespread. In West Texas the rate of use of water stored in the Ogallala aquifer far exceeds the rate of recharge, and along parts of the Gulf Coast large-scale pumpage of ground water has resulted in land-surface subsidence and salt-water encroachment. Problems of water quality, both from natural and man-made causes, affect the availability for use of water from portions of all of Texas' subsurface, water-bearing formations.

A major problem in Texas is the location of existing demands for water in relation to the location of available supplies. In many areas where existing water supplies are being depleted, or in which current water supplies are beginning to be exceeded by demands, there are not supplemental supplies available except at great distances. This problem is compounded by a limited availability and poor character of dam and reservoir sites. Thus, supplemental water supplies, either surface or ground, will often have to be transported great distances to meet demands.

Legal Problems

Water Rights

Among the problems in planning for redistribution of available surface water resources is the matter of existing water rights held under laws of the State. For the most part these rights represent a reasonable allocation of available waters from surface streams. However, this is not always true. There are some permits that are obviously and incontestably far in excess of projected requirements for water which holders of the permits may have. The Texas Legislature in 1967 enacted the Water Rights Adjudication Act to deal administratively with this problem. The Act authorizes the Texas Water Rights Commission to begin an orderly review of water rights throughout the State. This Act recognized that protection in perpetuity of all water rights, even though they are not exercised, penalizes other possible uses of the water to the extent of the difference between the actual needs and beneficial use of the rights holder and the full extent of the right. If these rights did, in fact, vest in the holder a right to a quantity of water from a fixed supply where beneficial use was not being exercised, then there would be no real possibility of balanced water planning. If, on the other hand, a water right carries simply the right to a supply of water to meet reasonable beneficial purposes, then the allocation and distribution of the waters of the State from various sources becomes possible through a system of management. It was on this latter concept, with built-in assurances of compliance with valid water rights as fully as they could be determined, that the Texas Water Plan of 1968 was formulated as a flexible guide to the development of the surface waters of the State.

Basins of Origin

The 1965 legislation authorizing development of a State plan explicitly forbade the formulation of any plan

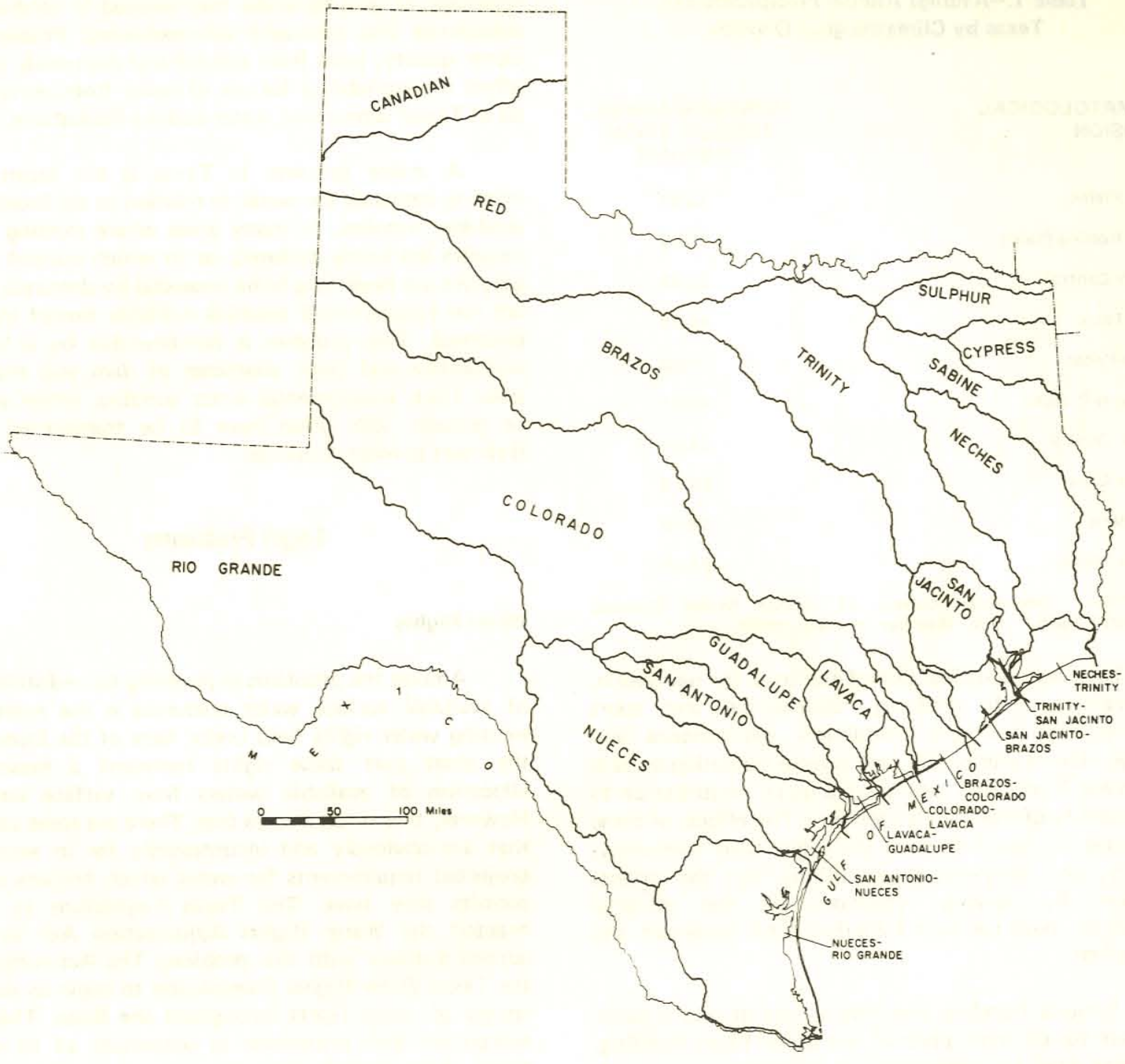


Figure 2.—River and Coastal Basins of Texas

"which contemplates or results in the removal of surface water from the river basin or origin if the water supply involved will be required for reasonably foreseeable water supply requirements within the river basin of origin during the next ensuing 50-year period, except on a temporary, interim basis." This constraint was built into all of the Board's planning considerations. As a result of this legislative intent the Plan, as it stands, offers the strongest protection against the depletion of river basin water resources through out-of-basin export to the detriment of in-basin users.

Compacts and Treaties

Four interstate streams, bounding or entering Texas, are regulated by compact between Texas and her neighboring states. These are the Rio Grande, Pecos River, Canadian River, and Sabine River. A fifth, the Red River, is in the process of compact negotiation. Additionally, the United States has entered two treaties with the Republic of Mexico that govern international waters of the Rio Grande. Provisions of all of these agreements were accepted as constraints in the Texas Water Plan of 1968.

Ground Water

Under Texas law, ground waters have been excluded in the past from management as public waters. This exclusion results from a variety of causes, some more valid in terms of hydrologic and developmental constraints than others. A local management technique for some aspects of ground-water development has been provided through creation of underground water

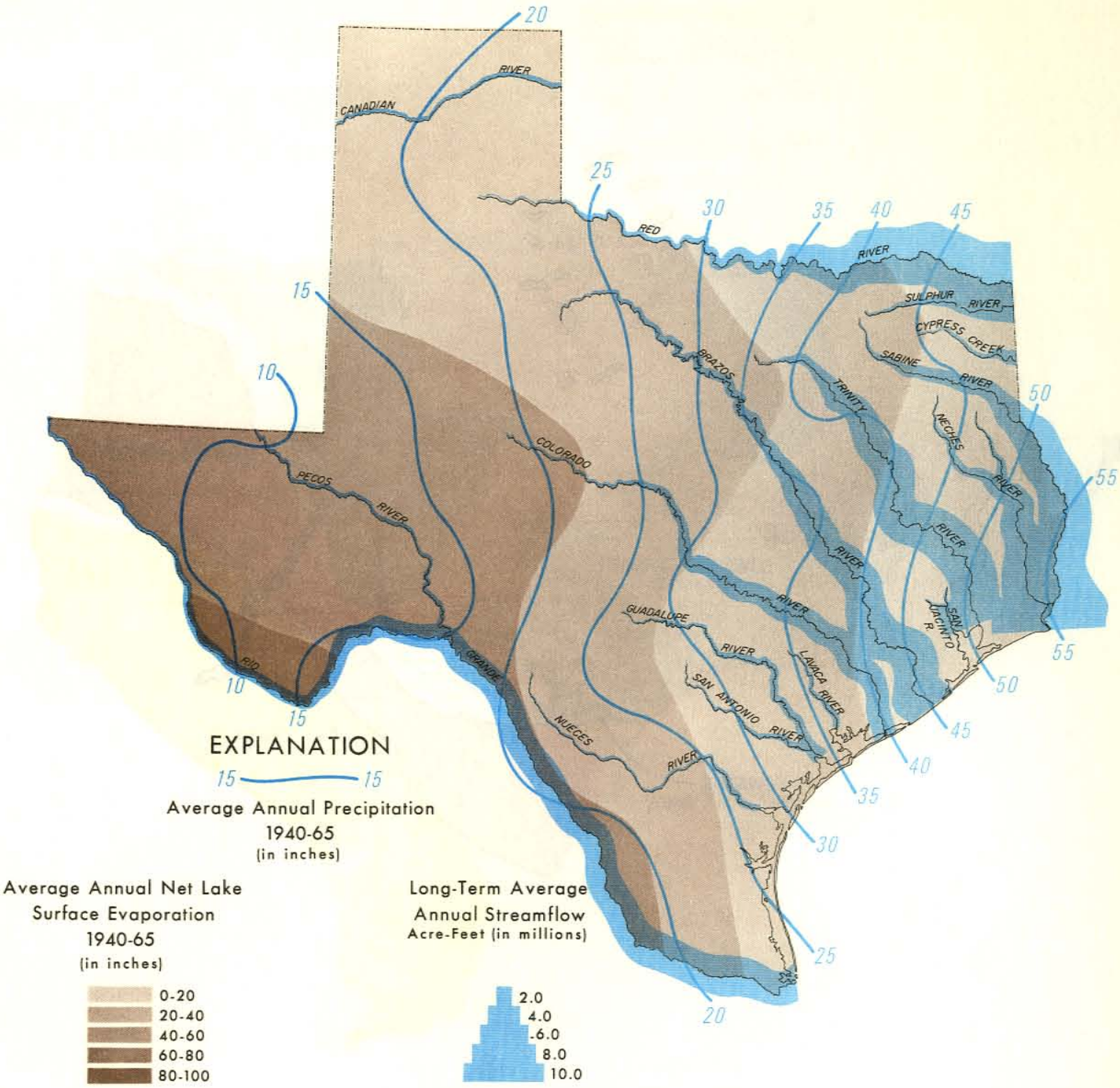


Figure 3.—Average Annual Precipitation, Streamflow, and Net Lake Surface Evaporation

conservation districts. The rationale behind the creation of these districts, with relatively broad administrative and taxing powers, was that in a state so large and diverse as Texas, the problems and needs of local areas could probably be met more effectively through local government.

Lack of a legal mechanism for management of ground water throughout the State has made some planning situations less amenable to solution than would otherwise have been the case.

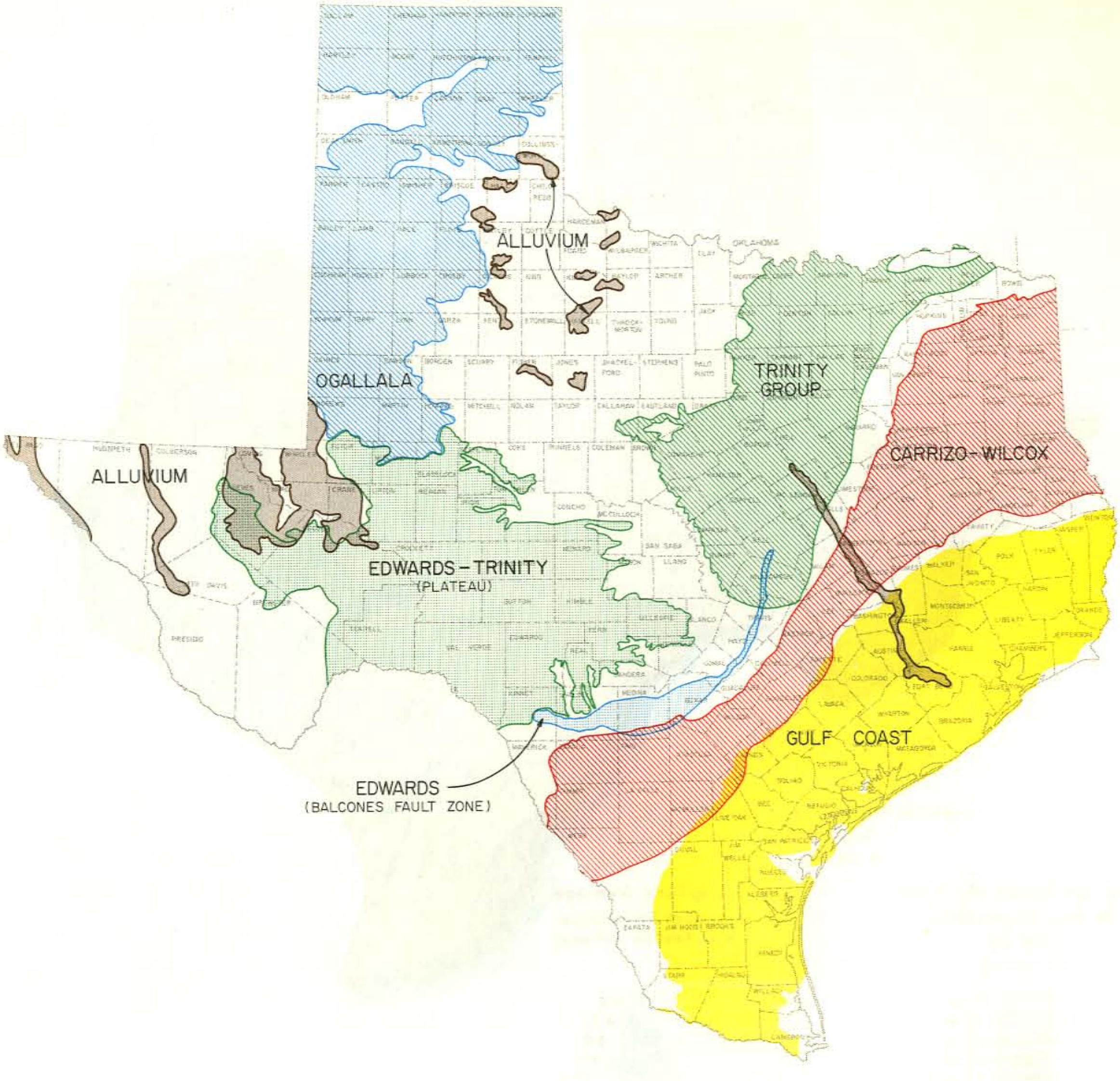


Figure 4.–Major Aquifers

II. PLAN DEVELOPMENT

Background and Authorization to Plan

Texas moved toward a realization of its need for long-range water planning through the impetus of a searing drought in the 1950's ended by devastating floods in the Spring of 1957. The first major governmental step was taken by the Texas Legislature in 1957 when the Texas Water Planning Act was enacted. Directives in that Act led to what was, in effect, an inventory of the water resources of the State; the data available for evaluating those resources; and recommendations for long-range programs needed to improve the planning and data-collection capability of the State water agencies in order to make rational planning and development of water resources a possibility.

A relatively short-term water plan was developed in 1961, proposing those physical structures required to meet municipal and industrial water supply needs through the year 1980.

A detailed plan was formulated in 1963 for approximately 60 percent of the State, excluding interstate river basins, by the U.S. Study Commission—Texas proposing project development to meet water needs through the year 2010.

These steps along the road to the development of a statewide water plan were useful, but none of them fulfilled the need for a comprehensive, integrated, statewide program of water development based on long-range projections of water problems and of water requirements for all purposes giving consideration to all intrastate resources and possible out-of-state sources.

In August of 1964, then Governor John Connally directed the Texas Water Commission to develop a statewide water plan for Texas. He said, "In the public interest and to aid the economic growth and general welfare of the State, I urge that you explore all reasonable alternatives for development and distribution of all our water resources to benefit the entire State, including proposals contained in the preliminary reports of the federal agencies."

In the year following Governor Connally's directive to the Texas Water Commission, the 59th Legislature undertook a massive realignment of the functions of the State water agencies, assigning to the Texas Water Development Board the responsibility for developing a statewide water plan. Under provisions of the Water Development Board Act, the Board was directed to "prepare, develop, and formulate a comprehensive State water plan." The Act further directed that the Board should be "governed in its preparation of the plan by regard for the public interest of the entire State. The Board shall direct its efforts toward the orderly development and management of water resources in order that sufficient water will be available at a reasonable cost to further the economic development of the entire State."

The Board was also directed to "give consideration in the plan to the effect of upstream development on the bays, estuaries, and arms of the Gulf of Mexico, and to the effect of the plan on navigation."

This Act recognized the need for flexibility in planning, and the importance of retaining options. The Board was instructed to "make such modifications and amendments to said State Water Plan as experience and changed conditions make advisable."

Planning History and Process

The Commission, and after agency realignment, the Board, approached the formulation of a long-range plan for Texas with an awareness that such a task required a broadly based approach. A multi-disciplinary planning organization was created within the agency. In addition, the Board created a Consulting Advisory Panel, the membership of which included planners of national repute. The Advisory Panel's purpose was to assist in developing a conceptual approach to the problem and a planning methodology adequate for its solution.

Developing this conceptual approach to planning required that the Board consider the planning factors and parameters significant to the development plans contemplated within the Board's understanding of overall State goals. These included water rights, priorities of use, criteria for water pricing, policies relating to the redistribution and reallocation of supplies, policies regarding project financing, and the interrelationships of Federal, State, and local agencies in water planning, development, and operation.

The major objective of the plan was to guide water development for the foreseeable future along lines which could be expected to produce the widest range of benefits for the entire State, while retaining to the maximum extent possible the range of options available as conditions change over time. Plan formulation was generally geared to the following concepts:

- planning for water resource development must, to the extent possible, be undertaken within the framework of broadly stated goals and objectives common to the region for which planning is undertaken;
- the objectives and potential impacts of alternatives of water resource development must be considered during the planning

process as an integral part of the entire social and economic developmental package relevant for the region for which planning is undertaken;

- The planner is not a decision-maker, and planning is not an end in itself. The planner is a part of an activity of government through which an orderly assessment of alternatives is presented to a public or publics in a form that makes it possible for that public to select from among alternatives with an awareness of the consequences of the choices made;
- planning for water resource development and management must address the entire range of water uses from the water source to the ultimate disposal of liquid-borne wastes resulting from water use;
- surface water and ground water are integral and interrelated parts of the total water resource system;
- the process of planning must be carried forward by an interdisciplinary team embracing the full range of expertise necessary for solution of the problem.

From the beginning, the Panel urged that the Board consider the use of the "systems" approach as an aid in the planning process. It recognized the advantages inherent in the use of more advanced and more sophisticated techniques for analysis of the complex and dynamic land and water resource system involved.

Traditional planning methodology has generally been directed toward analysis of projects individually in an effort to match project development with anticipated water requirements. When the interaction of individual projects became more pronounced and could not be ignored, project sizes and operating criteria were still selected on the basis of these single-project analyses through coordinated single-project simulation studies in which some incremental corrections on sizes of other affected projects were made. After trying several different configurations on the proposed projects, one configuration was selected as *the* plan based on economic, hydrologic, or other considerations. This traditional approach places heavy dependence on the experience and intuition of the planner and on the planner's ability to screen the less productive project sizes and combinations from the set considered in the "incremental analysis" used. If the total system is relatively simple, many incremental trials are made, the number of alternatives is small, and the planner's intuition and understanding of the problem is adequate, the traditional approach provides a viable basis for planning and decision-making. In the Texas planning situation, however, it was recognized by the Board and the Panel that this traditional approach was inadequate. The physical facilities that would be required would include a complex system involving a large number of dams, reservoirs, power plant diversion facilities, pumping plants, and navigation conveyance works and facilities, designed and operated to meet projected demands through 2020 for all purposes.

Water management considerations of flood control would be involved, and in addition the relationship of ground and surface water, and the impact of water quality on various uses would have to be considered.

Projected water requirements indicated that intrastate and interstate water resources available to Texas would have to be supplemented by importation, probably from the Mississippi River, by at least two routes if future water needs were to be satisfied.

Water storage and conveyance facilities would be constructed over time as demands for water grew. Proper sequencing, sizing, and staging of these facilities would have to be determined, with the objective that they be staged and operated as an integrated system capable of delivering, at minimum cost, the required quantities of water of suitable quality to the various users at any given point in time.

A methodology was required that would permit the following:

- Prediction of runoff in the various river basins, with consideration given to the changes in basin hydrology that will occur gradually over time as the consequence of changes in culture and pattern of stream control.
- Optimization of the physical configuration, sizing, and timing of the construction of the required transfer and storage facilities.
- Optimum operation of the facilities as an integrated system, though not necessarily including automation of physical operation.

Techniques were needed with the capability for handling:

- Reservoir operations with varying capacities.
- Reservoir yields under historical operation and modified for future conditions including systems operation of multiple reservoirs.
- Study of an entire river basin and multiple basins for storage of flows, reservoir releases, return flows from uses, unregulated flood and ground-water inflows, travel times between control points for a range from low to high discharges, quality of water in

reservoirs and streams, quality of return flows, sediment loads in streams upstream and downstream from reservoirs, flood control operations, hydroelectric power operations, changes on streams from natural conditions to navigation conditions with dams and locks, and requirements (water permit and projected future demands) for diversion at any location (from unregulated flows, reservoir releases, losses to aquifers, or directly from reservoirs).

- Information by comparison with present conditions for proposed future changes.
- Various water quality constituents.
- Expansion capability so that any number of reservoirs or other facilities could be added as needed.

With an appreciation of its need for this kind of methodological framework, the Board initiated a long-range research effort in 1967. The initial step was a request for proposals from consulting firms and universities for assistance in scoping the research program.

From the proposals received the Board selected five consulting firms to undertake the first step of conceptualization. These firms were Water Resources Engineers, Inc. of Walnut Creek, California; Harza Engineering Company and MacDonnel Automation Company of Chicago, Illinois and Houston, Texas; Texas Instruments, Inc. of Dallas, Texas and Bechtel Corporation of San Francisco, California; Hydrocomp, Stanford, California; and IBM, Inc. of Bethesda, Maryland.

The reports prepared by the consultants were extremely useful in shaping the research activity that followed. The Board submitted its first application to the Office of Water Resources Research in November 1967, proposing a three-year research effort at a cost estimated at $1 million. The initial proposal was for a study of the "System Simulation Of Interconnected Multiple River Basins and Ground Water Aquifers for Planning, Design, and Management of a Total Water Resource." In discussions with OWRR, the proposal was revised and divided into phases, with the research for the first phase using a component of the water resource system proposed in the unfolding Texas Water Plan as an example problem.

Subsequent phases dealt with resource allocation problems, economic measures of least cost as related to allocation of benefits, and methods of testing various social and economic alternatives. These latter phases have been partially funded by OWRR and the resultant models are described in subsequent chapters of this report.

The entire research program is summarized in this report. The intent was to develop an interrelated water resource planning package using the proposals of the Texas Water Plan as the example and test case, but having applicability elsewhere.

III. THE TEXAS WATER PLAN

The Texas Water Plan was released in December 1968. In accordance with provisions of the Water Development Board Act, hearings were held on the Plan by the Texas Water Rights Commission in April 1969 to assure that "...it gives adequate consideration to the protection of existing water rights in this State and whether or not it takes into account modes and procedures for the equitable adjustment of water rights affected by the plan." Following an affirmative finding by the Commission, the Plan was formally adopted by the Water Development Board and is—by law—a "flexible guide to State policy for the development of water resources" in Texas.

The Texas Water Plan, as formulated, proposes the development of a complex system of engineering and technical facilities. It includes recommendations for intergovernmental procedures and actions, legal considerations, economic and financial analyses, and a recognition of the environmental, social, and economic impacts of long-range water and related land resource development. Implementation of the plan requires a thorough and systematic analysis of a wide range of physical, social, and economic factors, and a more thorough analysis of alternative configurations of the physical system.

The key objective of the Plan is fundamental—to formulate a long-range comprehensive water plan for Texas that will meet the needs for water in all portions of the State. In meeting this objective, it was necessary to define the requirements for water in all parts of the State for all beneficial uses over a 50-year planning horizon, and the water resources that could be developed and used to meet these requirements. Figure 5 shows graphically those projected requirements.

In a preliminary Plan released in May 1966, the requirements for water to the year 2020 were projected, and a means was proposed for allocating and distributing the ground and surface waters available within the State to meet those requirements, to the extent that the requirements could be met. The preliminary Plan noted explicitly that those water supplies, including waters available to Texas from interstate streams, were not adequate to meet the long-range needs of the portion of the State lying west of the 99th parallel. The preliminary Plan emphasized the need to examine potential out-of-state sources to satisfy the objective of meeting water requirements for all of Texas.

On the basis of projections of water requirements to 2020 for all purposes—municipal and industrial uses, the maintenance of a viable irrigated agricultural economy, fresh water inflows to the bays and estuaries, mining, recreation, fish and wildlife, and other essential water uses—it was determined that approximately 32 million acre-feet of surface and ground water would be required annually in 2020.

The total projected water requirements for 2020 included over 12 million acre-feet of water annually for municipal and industrial uses, as compared to the 1970 municipal and industrial use of about 3.2 million acre-feet supplied from both ground and surface water. Over 16 million acre-feet of water was estimated as required annually for irrigation needs, increasing from the approximately 11.6 million acre-feet used for irrigation in 1970, again from both ground and surface sources. This projected irrigation demand was based upon a series of interrelated assumptions and constraints set forth in the Plan.

To meet these and other needs, approximately 12 to 13 million acre-feet of water annually would be required from out-of-state sources to supplement in-state ground and surface water supplies. Put another way, this means that after full development, distribution, and utilization of in-state water resources, Texas water requirements would exceed water supplies in 2020 by approximately 12 to 13 million acre-feet annually. The only known way of meeting this potential 12 to 13 million acre-feet shortage is by import of water from outside of Texas.

Several possible alternative out-of-state sources for an import on this scale were examined. Surplus water from the lower Mississippi River appeared to offer the greatest promise. The Congress authorized and funded studies by the Corps of Engineers to determine water availability in the Mississippi River, location and types of conveyance channels required to move surplus waters west, and the effects of withdrawals from the Mississipppi River. The Bureau of Reclamation was authorized to examine various routings through Texas for delivery of an import supply of water from the Mississippi to West Texas and eastern New Mexico.

The Texas Water Plan is based then on the following assumptions:

- The water resources of the State—both intrastate waters and those waters allocated and to be allocated to Texas under compact agreements—will be fully committed by 2020.
- Approximately 12 to 13 million acre-feet of surplus water annually will be available from the Lower Mississippi River (or other out-of-state source).

Physical Facilities

At the time the Plan was released, there were 157 existing and under construction reservoirs of 5,000 acre-feet or more conservation storage capacity. An additional 67 reservoirs or alternates and two salt water

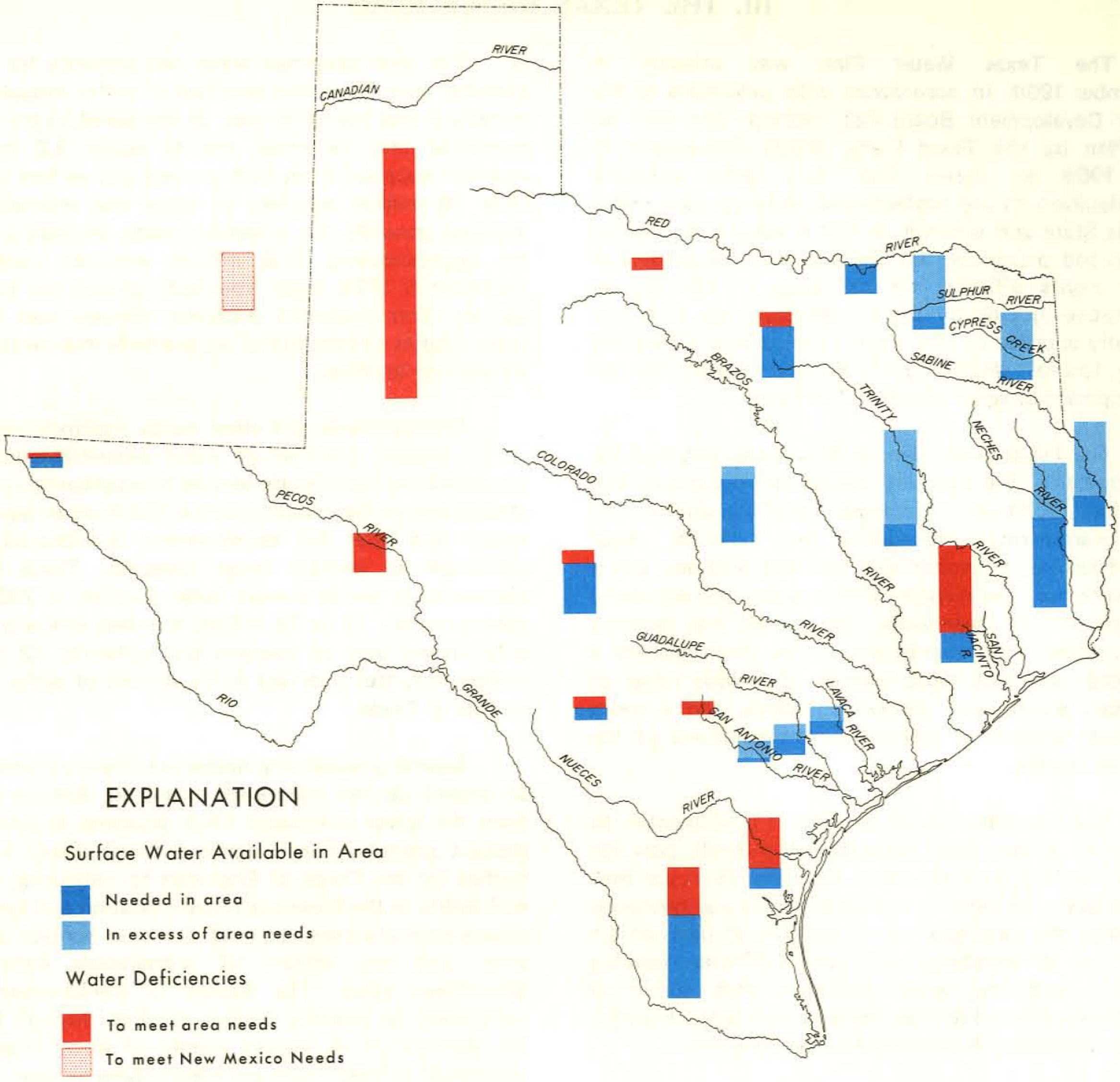


Figure 5.—The Texas Water Problem, 2020

barriers were proposed for development. Timing of construction of these reservoirs was proposed to be determined by the need for additional surface water supplies to meet requirements. Their construction was to be financed in whole or in part by Federal, State, or local interests, or by some combination of these. The proposed developments would provide water conservation storage, flood control capacity, and recreational and associated uses.

The Texas Water System

The Texas Water System comprises the reservoirs, conduits, and other facilities necessary to manage an imported water supply and the water resources of basins with interim or long-term surpluses, to meet intrabasin needs and to make the surpluses available for conveyance to areas of deficiency elsewhere in the State. The major components of the System include the Trans-Texas, Eastern, and Coastal Divisions.

The Trans-Texas Division, selected as the example problem for the Board's research activities, is shown in Figure 6. It includes 20 storage and regulating reservoirs and the interconnecting conduits and pumping stations in the northeast Texas river basins, the Trans-Texas Canal, terminal reservoirs in West Texas, and the wholesale distribution system.

In addition to meeting the intrabasin water requirements of the northeast Texas basins, the Trans-Texas Division would supply 350,000 acre-feet of water annually, for municipal and industrial uses, in the Dallas and Fort Worth area. It would convey 600,000 acre-feet of supplemental water annually through the

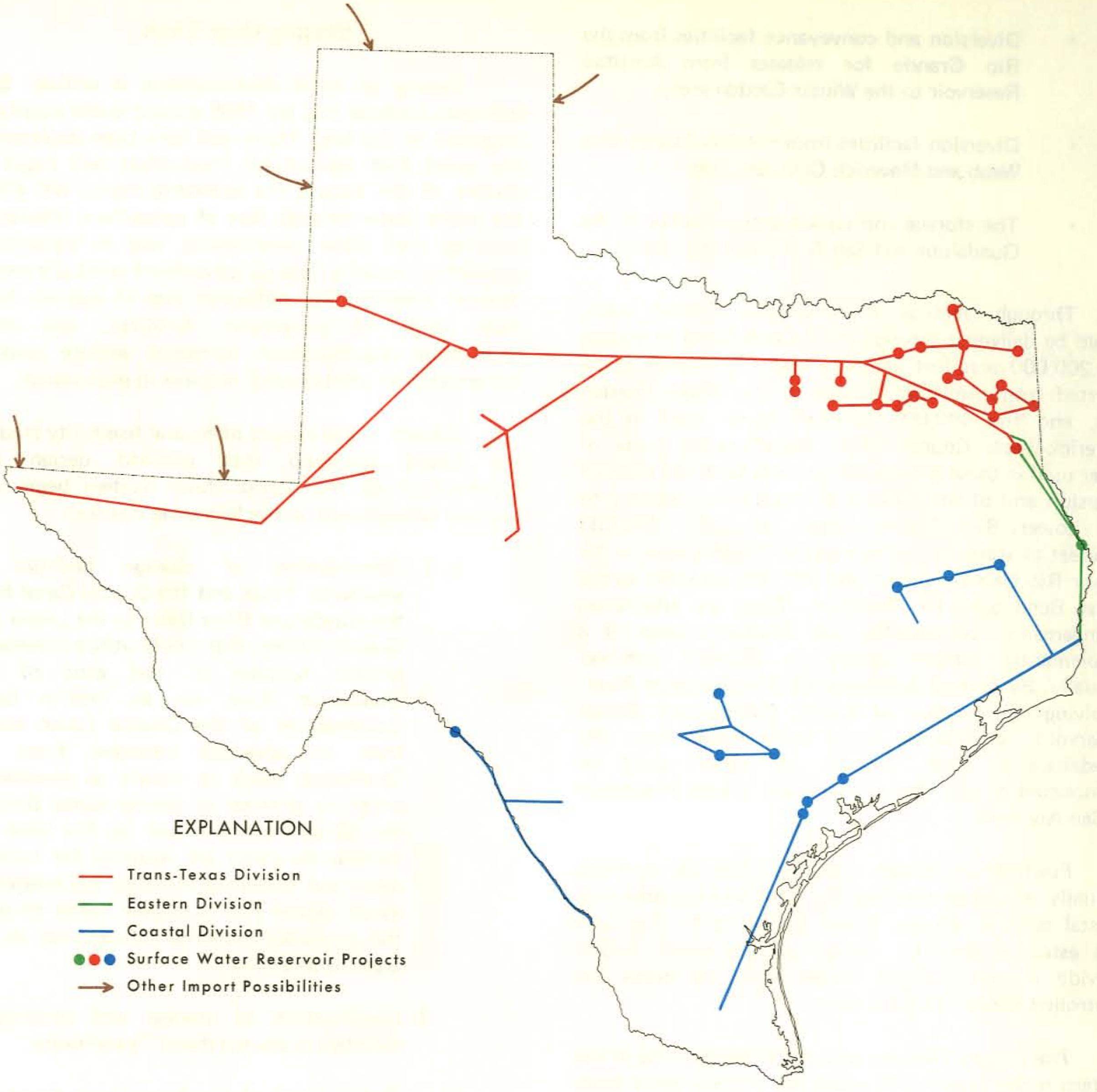


Figure 6.—Schematic Diagram of the Texas Water System

Trans-Texas Canal for municipal and industrial purposes to serve El Paso, Pecos, Odessa, Midland, Big Spring, Lubbock, Abilene, Sweetwater, Snyder, San Angelo, and Colorado City. Facilities of the Division would also carry annual deliveries of 933,000 acre-feet of water to supply irrigation in the Trans-Pecos area; 6,480,000 acre-feet for irrigation in the High Plains, and 171,000 acre-feet for irrigation in north-central Texas. Additionally, 1,500,000 acre-feet of water imported from out-of-state and delivered through the Division would meet water needs in eastern New Mexico.

Reservoirs in northeast Texas, where surplus yields would provide a part of the supply to the Trans-Texas Division, include George Parkhouse, Marvin C. Nichols, Texarkana, Cherokee Trail (formerly known as Titus County), Marshall, Black Cypress, Lake Fork, and Carl L. Estes (formerly named Mineola). It is estimated that these reservoirs, plus a planned diversion of 647,000 acre-feet of water from the Red River through Pecan Bayou Reservoir, would provide a dependable annual source of 2,593,000 acre-feet of water for redistribution to points of need. This water is surplus to foreseeable 50-year intrabasin needs.

The Coastal Division, important in later research phases, would include the following:

- The Coastal Canal to the Rio Grande basin with required storage and regulating reservoirs,
- The storage and conveyance facilities required to supply the Houston region,

- Diversion and conveyance facilities from the Rio Grande for releases from Amistad Reservoir to the Winter Garden area,
- Diversion facilities from the Rio Grande into Webb and Maverick Counties, and
- The storage and conveyance complex in the Guadalupe and San Antonio River basins.

Through facilities of the Coastal Division, water would be delivered through the Coastal Canal to replace the 200,000 acre-feet annually that is proposed to be diverted from Amistad releases to the Winter Garden area, and the 190,000 acre-feet to be used in the Maverick-Webb County areas. Reimbursable costs of water used in these areas would include both the costs of diversion and of the delivery of replacement water into the Lower Rio Grande Valley. Annually 700,000 acre-feet of water would be supplied for irrigation in the Lower Rio Grande Valley, and 727,000 acre-feet to the Coast Bend area for irrigation. There are alternative arrangements for meeting San Antonio's need of a supplemental surface supply of 220,000 acre-feet annually. By systems operation of the Guadalupe River, involving construction of Cuero, Cibolo, and Goliad Reservoirs, a pipeline could carry water from the Guadalupe to San Antonio, or, water could be transported directly from Cuero and Cibolo Reservoirs to San Antonio.

Fresh water inflows totalling 2,510,000 acre-feet annually would be supplied the bays and estuaries and coastal wildlife refuges. These quantities for the bays and estuaries may be revised as subsequent studies provide a more refined insight into the needs for controlled releases to these areas.

The Eastern Division includes those facilities in the eastern basins required to move out-of-state water from the point, or points, of delivery to the Trans-Texas and Coastal Divisions.

It was estimated that an import from out-of-state of about 8,400,000 acre-feet of water annually would be required to meet water needs of the Trans-Texas Division, and about 4,100,000 acre-feet would be required annually to meet the needs of the Coastal Division. The routing and facilities required to regulate this volume of out-of-state supply were to be determined in further studies.

Before construction of any conveyance unit of the Texas Water System could be initiated, assurance of an available import water supply is essential to avoid committing interim surpluses of in-state water supplies to meet needs in water deficient areas for which there would not be a sufficient assured long-term water supply without an assured out-of-state source of supply.

Staging Over Time

Timing of these developments is critical. Best estimates indicate that by 1985 ground water supplying irrigation in the High Plains will have been depleted to the point that agricultural production will begin to decline. If this occurs, the economic impact will affect the entire state—through loss of agricultural insurance, banking, and other investments; loss in agricultural productive capacity; loss of agricultural products moved through transporation networks; loss of markets for a wide range of equipment, fertilizer, and other agricultural appurtenances; increased welfare costs to those rendered unemployed; and loss in population.

Subject to the results of federal feasibility studies, the Board proposed that detailed design and construction of the Texas Water System begin and proceed concurrently in the following manner:

A. 1. Construction of storage facilities in southwest Texas and the Coastal Canal from the Guadalupe River Basin to the Lower Rio Grande Valley, that would utilize temporary surplus supplies in and west of the Guadalupe River on an interim basis. Construction of the Coastal Canal would then be advanced eastward from the Guadalupe River as rapidly as possible in order to attempt to deliver water through the Canal from the east by the time the interim surpluses are required for in-basin users and additional supplies are needed to assure delivery of sufficient water to meet the projected build-up in demands in the areas to be served.

2. Construction of storage and conveyance facilities in the northeast Texas basins.

B. Construction of the Trans-Texas Canal and storage projects and municipal, industrial, and irrigation distribution facilities in the High Plains and north-central Texas areas. (Construction of irrigation distribution systems in the High Plains would have to be initiated before completion of the Trans-Texas Canal and Caprock and Bull Lake Reservoirs.) As the construction of the Trans-Texas Canal to Caprock Reservoir and the canal to Bull Lake Reservoir were completed and construction begun on the main canal southward toward the Pecos River basin, construction would have to begin on the irrigation distribution system in the Trans-Pecos area.

C. Construction of the conveyance facility from the Mississippi River to the State line.

In the Trans-Texas Division, surplus water supplies from the northeast Texas basins would be conveyed westward first. These surpluses would supply the projected requirements in the Dallas-Fort Worth area as needed, and deliveries could be initiated through the Trans-Texas Canal to north-central and West Texas.

As conveyance facilities from the Mississippi River were completed, the additional imported water, plus the 1.5 million acre-feet annually for New Mexico, would be moved through the Trans-Texas Division facilities as rapidly as municipal demands increase and as irrigation distribution facilities are constructed to serve the areas.

When the Coastal Canal is completed east to the Sabine River, Mississippi River water would be brought directly into the Coastal Division to supplement in-state supplies transported through the Canal, thus supplying all projected 2020 requirements in the areas to be supplied by the Coastal Division. At this phase the Texas Water System would be fully operational.

The Plan is an extremely large, complex, and costly proposal of potential means to meet the predicted water requirements of Texas to the year 2020. Obviously, the various portions of the Plan require much additional and more detailed analysis. More sophisticated and comprehensive planning capabilities are required to perform the analysis of the many Plan alternatives. The following chapters describe the research undertaken by the Texas Water Development Board, with partial financial assistance from the Office of Water Resources Research, to develop these capabilities.

IV. PLANNING METHODOLOGY FOR WATER RESOURCE DEVELOPMENT

Introduction

The demands on water resources for municipal and industrial supplies, hydropower generation, irrigation, quality management, flood control, recreation, fish and wildlife protection and enhancement, and achievement of environmental objectives have continually increased through time. Planning for water resource development has become necessary at all governmental levels as demands on water resources have increased and become more diverse. More and more clearly water resource planners are recognizing the need to integrate the objectives for water resource development with broader social and economic objectives to achieve regional, statewide, and national goals.

The multi-objective approach to planning has as its purpose the systematic examination of alternative solutions to water resource problems for the purpose of determining the relative benefits and costs of each alternative in terms of achieving the recognized objectives of national economic development, environmental quality, and regional development. While the objectives are not mutually exclusive, their concurrent consideration—and plan formulation for achieving a satisfactory mix—requires a series of judgments that balance benefits against costs, and consider resultant tradeoffs until an acceptable solution is reached.

Comprehensive planning for efficient development of water resources on the scale contemplated in Texas requires a continuous process of decision-making; seeking the "optimal" development and allocation of the resource within a complex framework of technological, economic, social, and institutional conditions and constraints. The decisions to be made must be approached with objectivity and must have been arrived at only after thorough consideration of the alternatives. While the ultimate decision may be subjective or judgmental because of the intangibles involved, it may be considerably reinforced by a careful analysis of the consequences of alternatives.

The number of alternatives, restraints, and decisions in regional planning is extremely large. Thus, sound analytical techniques for their consideration must be established. In recent years techniques have been developed which greatly enhance the capabilities of the decision-maker to cope with these otherwise intractable problems. Among these are the techniques of:

- mathematical modeling of water storage and conveyance systems,
- simulation on digital computers of system operation,
- organization and systematic handling of data, and
- optimization techniques for design and operation of systems.

System simulation is costly and time-consuming. As a consequence data needs require careful attention at the preliminary planning stage, since the adequacy of the data base—hydrologic, water quality, economic, etc.—is vital to the successful application of system simulation techniques. Construction of the required data base must be approached conjunctively with formulation of mathematical models. In addition, the mathematical models are of considerable value in the development of a data program.

An important phase of planning concerns evaluation of alternatives. "Near optimal" systems or schemes of operation are sought, with special attention to the many restraints likely to be imposed. The approach is basically that of modeling mathematically a complex real system. Thus, realistically absolute duplication of the prototype is not anticipated. Only a reasonable simulation can be expected. Tests of reasonableness, verifying the model against the prototype, invariably involve the exercise of judgment, especially when sufficient reliable data are not available.

Models, of whatever form, are tools which if properly designed can perform many of the tasks of water resources planning and system implementation. Models are not ends in themselves. To be of maximum value they are needed early in the planning phase when important decisions must be made. Consequently, selection of model type itself becomes a critical and important step in the systems approach to planning.

Interaction Between Planning and Systems Analysis

Planning and systems analysis are two distinctly different activities. Planning involves the perception of problems, formulation of problem statements, identification and listing of possible alternative solutions, selection of methods to evaluate alternatives, specification of data requirements and acquisition of data, and empirical evaluation of alternatives. The planner must select the "best" or most acceptable solutions from among the alternatives, display these to decision-makers and, if instructed, implement a course of action, observe the results and assume responsibility for the outcome.

The systems analyst or engineer actually conducts the empirical evaluation of the alternatives and reports the results to the planner(s). Thus, system analysis can only provide information within and as a part of the planning process.

The systems analyst may participate in the selection of methods of evaluation, and is responsible for expressing the methods in suitable form for calculations including the mathematical and statistical forms of equations which relate the factors to be considered. He must select or develop computerized solution techniques, acquire data, perform data processing, solve and test the models, and conduct a systematic solution of models using a range of values of the data to determine sensitivity of solutions to individual variables and to variability of the data.

The systems analyst reports the results to the planner for use in planning. The planner, based on the results of the systems analyses, may vary the forms of the alternatives to be considered, or specify new alternatives to be evaluated. In that case, the systems analyst returns to work following the same procedure and brings forth a new set of results. This process of evaluation may continue through several rounds or iterations until the planner is satisfied that the relevant range of alternatives has been considered or until a suitable solution has been obtained.

Thus, although the systems analyst is an integral element of the planning process, the analyst only provides the empirical information required by the planner, after the planner has specified the alternatives and posed the questions to be answered. It is the role of the systems analyst to assist in the specification of the relationships among the variables, i.e., formulate the models of the systems to be analyzed, choose the solution techniques appropriate for the problem at hand, acquire the best available data, and conduct and report the analyses. The planner must, by the same token, understand the capabilities and limitations of the models and techniques used by the analyst for analysis of the planning alternatives.

Systems analysts are concerned with highly sophisticated operations research techniques and simulation models, while planners are concerned with the perception of problems and the alternatives of society for solving the problems. This does not mean that systems analysts are unconcerned with problems and alternatives or that planners are indifferent to the methods and procedures of systems analysis. In order to be effective each must be aware of the problems and methods of the other and above all else each must have respect for the other.

Planning Methodology

Briefly then, through this interaction process, the following steps take place in a planning situation in the public sector:

Perception and Delineation of the Problem

The planner, together with appropriate public sectors and governmental agencies, perceives a problem within a particular geographic unit. In the field of water resources this problem may involve a potential water supply shortage, flooding hazard, water quality impairment, a need for water oriented recreational facilities, or other similar needs or combinations of needs. The extent and immediacy of the problem are defined and articulated.

Definition of Broad Goals and Objectives

The planner, public interests, and governmental entities establish the values—objectives—goals to be achieved by advancing a tentative plan for solution of the problem. While the instant problem may be limited to a single purpose of water resource development, i.e., serving a water supply need or alleviation of flood hazard, the broad objectives and goals to be achieved must be thought through in the context of a multipurpose concept of water and related resource development. In this sense, resource development may be used as a tool for achieving social, economic, and environmental objectives. If planning were limited to the narrow objective of solving an immediate problem, the long-range benefits of planning for other purposes is lost.

Selection of Alternatives to be Considered

It is at this point in the planning process that the public sector planner must accept the obligation of specifying the alternatives, recognizing the imprecision of his tools for selection, and simultaneously recognizing that the final selection from among the alternatives will ultimately be made through the political process. The Water Resources Council's proposed "Principles and Standards" for project evaluation, as originally conceived, were designed to provide an orderly means by which the alternatives achievable through water resources development could be examined in a meaningful way. The planner must—through an objective examination of the problem defined, and the resources available for solving the problem—determine what alternatives are available for achieving the desired objectives. This examination—and it must be a creative examination—should make possible at a conceptual level these determinations:

- the water requirements that are to be met over the full term of the planning period;
- the range of purposes that could be served by full development;
- the water resources available, or that could be made available;

- the alternative physical works, or other means, for matching available resources to the needs for use of those resources.

Selection of Planning Methodology and Planning Objective, Criteria, and Constraints

The techniques of systems analysis have made possible a sophistication of planning which a decade ago was unobtainable. However, in the interaction between the planner and the systems analyst some inherent dangers must be recognized. The constant redefinition of the planner's role and responsibility will serve to eliminate the principal danger—that of the systems techniques' tail wagging the conceptual planning dog. The planner, in cooperation with the systems analyst, must do the following things explicitly:

- define and describe the problem;
- state the broad objectives to be achieved by the plan finally recommended;
- define the possible resources and the broad alternatives to be evaluated in the planning process to meet these objectives;
- define the absolute constraints to be imposed on alternate solutions such as water rights, minimum streamflows, quality limitations, etc.;
- define the ranges of parameters for which evaluations are to be made;
- state the specific planning decisions for which information is required from the systems analyst and the sequence in which the information is to be furnished in order that planning decisions may be made in the proper order during the planning process; and
- define the type, extent, and detail of the information to be furnished by the systems analyst.

Development of Data Base

Throughout the planning process, the planner is confronted with the problem of limited data. This limitation sharpens the focus on the planning responsibility—at the stage where planning decisions are demanded by the exigencies of the problem, those decisions must be made on the basis of the information at hand. This requirement of the planner does not, of course, mean that he must not or should not take all possible steps—without postponing necessary action—to assure that an adequate data base is available. It does mean that the planner must recognize that there is no need for planning after the fact, and that as a consequence he will always be obliged to temper existing knowledge with interpretative judgment and intuition.

Data management, as used here, refers to the total program for observing, collecting, recording, storing, retrieving, and preparing for use all relevant data as they are required. In developing a data base adequate for support of the planning process, the needs of that process must be carefully evaluated by the planner, systems analyst, and others. Decisions must be made as to the range of facts required for planning support, the level of detail and accuracy of data acceptable for the planning answers sought, and the categorization of this knowledge for rapid and efficient access. These requirements have become more stringent as the voracious appetite of systems analysis techniques and large-capacity computers have pushed the possibilities of data manipulation to hitherto unexplored areas.

Plan Formulation, Analysis, and Evaluation of Each Alternative

The planner and systems analyst are ready at this stage to "put it all together." The planner will set forth for the systems analyst the series of alternative plans conceived within the framework of achieving the broad objectives. Applying the selected analytical methodologies, the systems analyst will then through an iterative analytic process, consider the following:

- Using a range of population and economic projections specified by the planner, the probable levels of projected water requirements for all purposes for the full term of the planning period.
- Intermediate requirements for intervening selected time increments.
- All sources of water supply that are—or could be made—available to meet these levels of water requirements.
- The possible alternative configurations of supply and demand.
- For each such alternative, the benefits and costs determined through a system of accounts identical or similar to that proposed in the Water Resources Council's "Principles and Standards."
- The value of each alternative in terms of achievement of the defined multi-objectives.

As this analytic process develops, the planner must make a series of decisions in response to the results of the analysis. Adjustments and reformulation of alternatives will be required as the planner attempts to focus more sharply on the optimal mix of alternatives. Results of the analysis may cause the planner to select new alternatives.

Selection of Recommended Alternative

The planner and systems analyst together select the alternative plan which most nearly fits the optimum solution to the initial problem in the context of selected objectives. Through various techniques, the relative costs and benefits, as well as the total impact of the alternatives examined, must be displayed and presented in a form meaningful to the decision-making entity.

Decision

The decision-making entity, whether it be the Congress, a state legislature, or other public sector, may accept or reject the planner's work in whole or in part. The decision must be based on consideration and understanding of the broad goals and objectives, the alternatives selected by the planner, and the recommendations of plans to solve the problem for which planning was authorized and undertaken. If the plan is rejected at this decision stage, the planner must work with the decision group to identify the divergence between the recommended plan and an acceptable plan. He must then return to that point in the planning process indicated by the cause of rejection in order to begin the evolution of a plan that will be acceptable.

The research program of the Texas Water Development Board, as described herein, is designed to provide the Agency with enhanced capabilities for these analytic processes, thus resulting in improved information for decision-making by the Board and Texas State Government. The systems analysis and data management capabilities presented in the following chapters permit a detailed analysis of many more alternative plans than was previously possible. By analyzing more alternatives, in more detail, it is possible to present the planners and decision-makers with a wider range of options and a better idea of how these options would perform in meeting specified goals.

V. THE PLANNING TECHNIQUES AND THEIR APPLICATION

Introduction

The three-phase Office of Water Resources Research-funded research effort has resulted in the development of a series of computer-oriented planning models and application techniques which can be used to analyze a variety of water resource planning problems and alternatives including many problems identified in the Texas Water Plan. These models and techniques have been developed so as to be functionally interactive in the planning process. Equally important, this research effort has spawned the development of companion techniques, funded entirely with State funds, to provide analytic capabilities for the total spectrum of problems encountered when planning the use of scarce water resources; e.g., ground water management and environmental effects of water resource development.

This discussion of these models, their potential applications, and their limitations is not intended to be detailed or all-inclusive. Instead, it summarizes the Board's experience in the application of these systems analysis techniques to water resource planning investigations. More detailed information is presented in the three project completion reports (Texas Water Development Board, 1970, 1971b, 1974) which describe the techniques and models summarized herein.

Simulation of Surface Water Systems

The major emphasis of the research was on the development of computerized models for planning large-scale, multibasin surface water resource systems. Three prinicpal models were developed—SIMYLD-II, SIM-IV, and AL-III. An additional model—RESOP-I—which was developed prior to the OWRR research project can be used to analyze the detailed operation of a single reservoir.

RESOP-I

To facilitate individual river basin planning studies, and as a part of the overall research activity, the Texas Water Development Board developed a reservoir operations program (RESOP-I) that determines the firm yield of a single reservoir. Firm yield is defined as the annual quantity of water that can be obtained from a reservoir without drawing it down below the minimum conservation pool. Using RESOP-I, the annual demand can be distributed throughout the year in any monthly pattern; up to 25 years of reservoir operation can be simulated using monthly time periods, and the program can accommodate a maximum of 10 reservoir sizes as a means of analyzing the relationship between reservoir size and firm yield.

The program can also be used to simulate the operation of a reservoir using annual demand rates that are different from the firm yield. When used in this manner, the program also simulates the behavior of conservative mineral constituents in the reservoir, and predicts the quality of water supplies as well as reservoir releases.

Input data requirements for RESOP-I fall into the following three general categories:

Reservoir Characteristics

- Latitude and longitude of reservoir,
- minimum and maximum conservation pools,
- area-capacity data, and
- initial reservoir storage (and quality constituent levels).

Hydrologic Inputs

- unregulated reservoir inflows (and qualities),
- upstream reservoir releases (and qualities), and
- reservoir evaporation rates.

Demand Coefficients

- A set of 12 numeric values, representing the fraction of the firm yield (or annual demand) that is to be satisfied each month. The value of the coefficient depends upon the use to be supplied (agriculture, domestic, individual, etc.).

Evaporation rates are obtained from a master data file maintained by the Board. The file contains monthly evaporation rates for the entire state. The information needed to obtain these data is the latitude and longitude of the reservoir site.

Figure 7 shows the result of applying the reservoir operation program to determine the firm yield of a proposed reservoir. Upstream development assuming 2010 land use and water use conditions were used in this analysis.

Figure 8 illustrates the application of the reservoir operations program to simulate the temporal behavior of chloride in Lake Stamford during the period 1954 to 1963. The peaks reflect periods of low streamflow conditions.

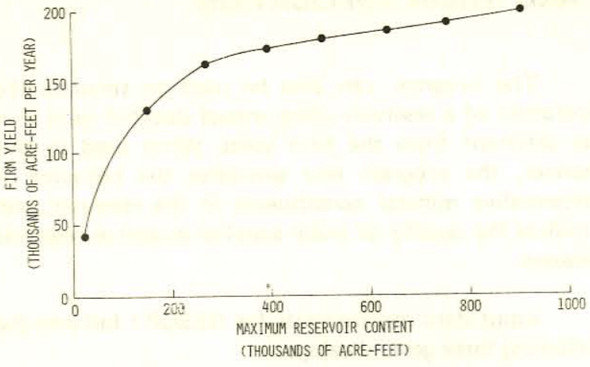


Figure 7.—Estimation of Firm Yield With RESOP-I

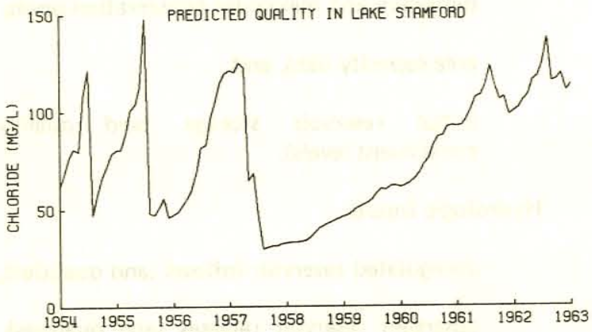


Figure 8.—Prediction of Water Quality With RESOP-I

SIMYLD-II

SIMYLD-II was developed to provide the water resource planner with a tool for analyzing water storage and water transfer within a multireservoir or multibasin system. The model was designed to simulate both small-scale systems, such as two or three reservoirs within one river basin, and large-scale systems having more than one reservoir per river basin and more than one river basin, such as the proposed Texas Water System.

SIMYLD-II provides capability for two basin planning analyses. The first is the simulation of the operation of a system subject to a specified sequence of demands and hydrologic conditions. The model simulates catchment, storage, and transfer of water within a system of reservoirs, rivers, and conduits on a monthly basis with the object of meeting 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, it is spatially located at the lowest priority demand node(s).

The second planning use of SIMYLD-II is determination of the firm yield of a single reservoir within a multireservoir water resources system. Firm yield is defined as the maximum quantity of water a reservoir can be expected to deliver per unit time during the longest historical period of drought (period of lowest runoff of longest duration). 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, since spills from some reservoirs can be stored in other reservoirs. An iterative procedure is used to adjust the demands at each reservoir in order to converge on its maximum firm yield at a given storage capacity assuming total systems operation.

The model is designed for maximum flexibility in selecting operating rules for each reservoir. The operating rules are formulated as the desired percentage of the reservoir capacity (either total or conservation) to be held in storage at the end of each month. A priority ranking can be assigned to each storage reservoir. This ranking is then used to determine the allocation of water between meeting demands and maintaining storage. The planner using the model has enough flexibility that he may vary the desired monthly reservoir storage levels during the year and the priority of allocation of water between satisfying immediate demands and maintaining storage in the reservoirs by changing the operating rules.

SIMYLD-II can analyze either static or dynamic system operation, permitting use with either constant or time-variable demands. In addition, the planner can use the model to analyze the operation of the system under the expected ultimate demands for any selected hydrologic sequence.

The mathematical concept underlying SIMYLD-II is that the physical water resource system can be transformed into a capacitated network flow problem. In making this tranformation, the real system's physical elements are represented as a combination of two possible network components—nodes and links. Given the proper parametric description of these two network components, it becomes a straightforward task to develop the necessary capacitated network. Once developed, the network system can be analyzed as a direct analog of the real system.

As the nomenclature implies, a node is a connection and/or branching point within the network. Therefore, a node is analogous to either a reservoir or a non-storage junction (i.e., canal junctions, major river intersections, etc.) in the physical system. Additionally, a node is a network component which is considered to have the capacity to store a finite and bounded amount of the material moving in the network. In the case of SIMYLD-II, reservoirs are represented by nodes which have a storage capacity as well as the ability to serve as branching points. A non-storage capacitated junction is handled similarly to a capacitated junction (reservoirs) except that its storage capacity is always zero. Demands placed on the system must be located at nodal points.

Also, any water entering the system, such as might occur naturally from runoff or artificially through import, must be introduced at a nodal point.

The transfer of water among the various network nodes is accomplished by transfer components called links. Typically a link is a river reach, canal, or closed conduit with a specified direction of flow and a fixed maximum and minimum capacity. The physical system and its basic time-step operation, in this case a month, is formulated as the network flow problem. The set of solutions to this network flow problem provides the sequential operation of the system with the set of monthly operations becoming the operation of the system over the length of a hydrologic sequence.

An initial step in the application of SIMYLD-II is the construction of the node-link diagram describing the physical system. Figures 9 and 10 illustrate a typical river basin and its node-link diagram. After the water resource system problem is represented as a network flow problem it is solved using a mathematical technique known as the out-of-kilter algorithm. This algorithm optimizes the transfer of water in the network, based on transfer costs. The algorithm operates by defining conditions which must be satisfied by an optimal "circulation" in a network—a flow which satisfies capacity restrictions on all arcs and also satisfies specified conservation of flow conditions at all nodes. When such a circulation is obtained, all arcs are said to be "in-kilter." If, at some point during the solution, such a circulation does not exist, some arcs are "out-of-kilter." An iterative procedure is used to bring the "out-of-kilter" arcs "in-kilter", if possible. The algorithm then proceeds to the next time step (Durbin and others, 1967). In the case of SIMYLD-II, the user-specified priorities for meeting demands for water and the priorities for storage of water in the reservoirs are used as the optimization criteria. More detailed descriptions of these techniques are given in Texas Water Development Board Reports 118 and 131.

The SIMYLD-II model requires the following types of input data:

- Basin Description
  - reservoirs and demand points
  - river reaches, canals, and pipelines
- Reservoir Data
  - initial capacities
  - area-capacity curves
  - upper and lower limits of conservation pools,
- Input and Demand Information
  - reservoir inflows
  - evaporation rates
  - monthly demand coefficients

An analysis with the SIMYLD-II model provides the following: (1) a time history of the optimal operation of the surface water system including reservoir storages, water transfers, and spills from the system, and (2) the demands met and shortages incurred during the simulation period. Figure 11 shows a typical multireservoir analysis using the SIMYLD-II model. The curves shown represent the type of yield response to be expected from a system of reservoirs with and without pump-back capability. The bottom curve shows the firm yield for the total basin storage without pump-back capability. The top curve shows the same system with pump-back capability. The figure shows that increased basin yield can be obtained with the pump-back capability.

The SIMYLD-II model has already been used in a number of applications involving river basin problems. These include; providing analytical information to the Texas Water Rights Commission to assist in the adjudication of water rights in the Cypress Creek basin; analytical studies of basin firm yields and interbasin water transfers in support of the Board's studies of the proposed Coastal Canal, and basin yield studies of the existing and proposed reservoirs in the Nueces River basin to provide information to the Texas Water Rights Commission on permits for proposed reservoirs. In addition, the model has been provided to a number of public and private entities throughout the United States for use in planning and management of water resources.

SIM-IV

SIM-IV is a computerized procedure designed to simulate the operation of a large complex surface water storage and transfer system. The system can be either static or dynamic in nature, in that over time water storage and transfer facilities can be constant or can increase in size. The SIM-IV computer routine allows individual network system elements to be introduced at any point in the simulation time span. This capability provides the option of investigating various patterns of construction schedules in order that the least costly can be selected for implementation. These capabilities allow SIM-IV to be used either as a stand-alone procedure or as an extension of any staging analysis.

SIM-IV is the most advanced form of the simulation models developed during the three-phase research project. Its immediate predecessor, developed in

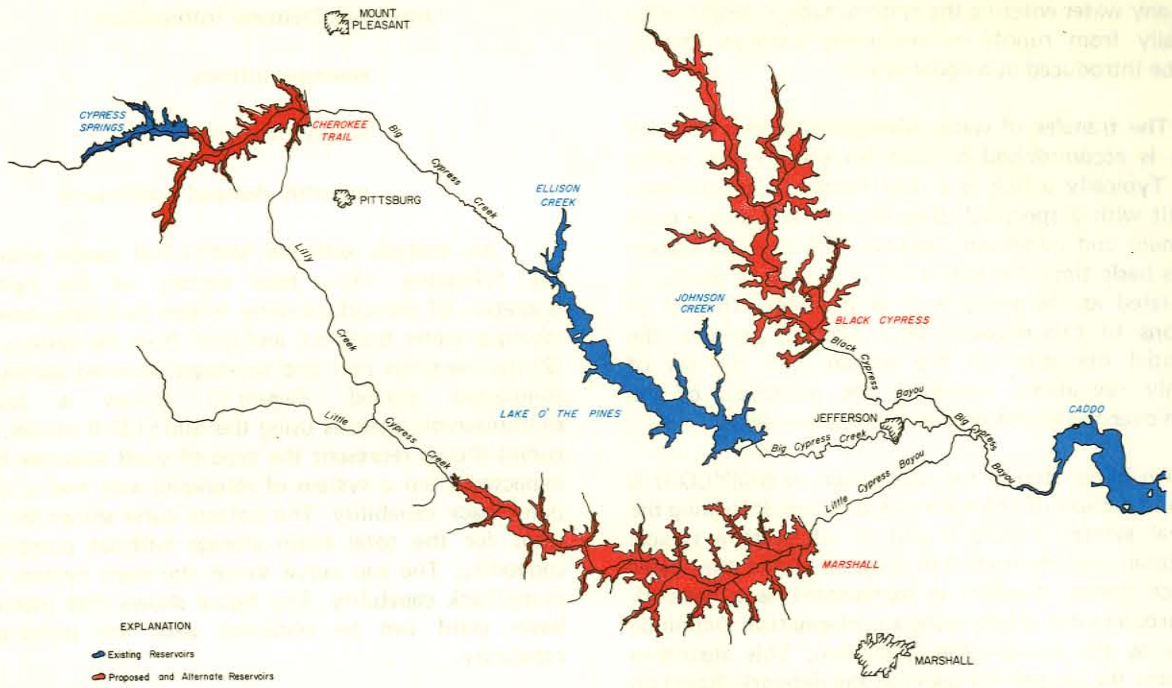


Figure 9.—Cypress Creek Basin

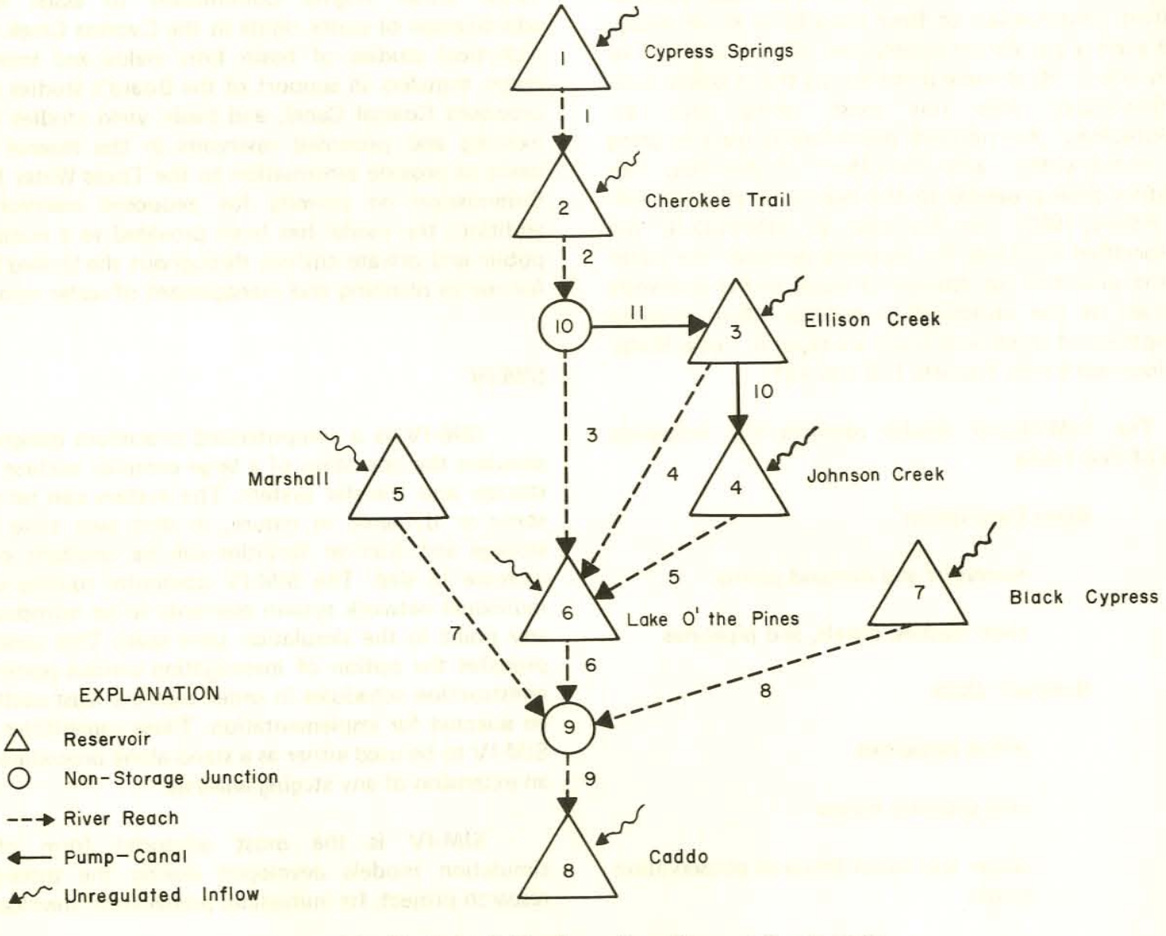


Figure 10.—Node-Link Configuration, Cypress Creek Basin

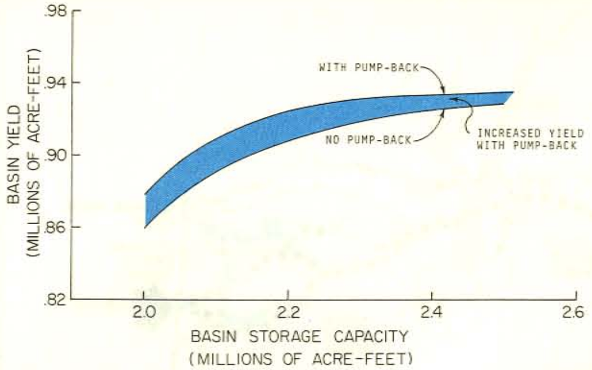


Figure 11.—Typical Multireservoir Analysis With SIMYLD-II

the second year of the research project, was the SIM-III model. SIM-IV differs from SIM-III in that SIM-IV contains an improved method for representing reservoir operating rules and has a means for permitting the quantity of water stored in the system at the beginning of the crop growing season to be taken into consideration when planning solutions are being sought to meet the entire seasonal demands for agricultural waters.

SIM-IV uses a representation of a surface water resource system exactly like that used by SIMYLD-II which was previously described. However, SIM-IV contains a procedure for minimizing the operational cost of fluid transfer within a capacitated network. A solution is produced for a finite time interval (one month), and the analysis moves forward in time in a stepwise fashion. Within the network, demands for the material in transport are made at any network junction and the amount of material in storage at each junction is constrained by specified limits. The assumption is made that the unit cost of transport is known at all points in time and space.

The network flow problem, as analyzed by SIM-IV, is stated in exactly the same manner as for the SIMYLD-II model. However, in SIM-IV, capital costs are entered individually for each system element (canal and reservoir) and system operating costs are computed by the model. In general, the movement of water via the transfer links will be done at a cost which is a known funciton of the quantity of water flowing and the pumping lift. It is the function of SIM-IV to meet system storage requirements and system demands while minimizing the cost of transporting water within the system. No water will be spilled from the system if storage capacity remains in the reservoirs.

Conceptually, SIM-IV follows these steps in moving from a known set of state variables at the beginning of a time period to the solution for a required set of state variables at the end of the time period:

- The present status of the network is evaluated and all existing system elements are given an appropriate parametric description or numeric value(s). Non-existing but potential system elements are given zero values for all characteristics (storage, flow, etc.).
- All specified hydraulic and hydrologic inputs and demands are accounted for, and the mass balance for the entire network system is determined. Bounds are placed on system demands, spills, and storage levels.
- The flows necessary to meet the levels required and at the same time minimize the system's total cost of water transport, are determined through the application of an optimization procedure.
- All necessary state variables have now been determined, and the status of the system at the conclusion of the current time period becomes the status at the beginning of the next time period.

This procedure is repeated in a stepwise fashion until a specified simulation interval has been spanned.

The SIM-IV model assumes that future hydrology is unknown, that is, it operates from month to month without any knowledge of coming events. It requires that the planner, based on his knowledge of the system, determine where he would like to store excess water in any given time interval. Since SIM-IV uses the out-of-kilter algorithm to solve the problem, the planner's preferences are translated into negative costs on the network arcs. This is explained in detail in Texas Water Development Board Report 118. These negative costs play no role in competing with meeting demands or selecting optimal paths in the network, but they allow the system to move water in advance of demands to selected storage sites. This pricing policy remains constant for the entire simulation period and is independent of the variations in yearly hydrology.

Demands for water can be specified prior to simulation, or, in the case of irrigation demands, can be expressed mathematically as a functional relationship in which the quantity of water demanded depends upon the quantity of water in the supply system. More detail about these functional relationships between the water supply and irrigation demand variables is provided in the next section of this report and in Texas Water Development Board Report 179.

The SIM-IV model was applied to the multibasin surface water resource system of the proposed Trans-Texas Division of the Texas Water System, for purposes of illustrating the model's capabilities. Figure 12 illustrates this example problem in it's actual network from. Typically, the analysis of a surface water system using SIM-IV provides the following information: (1) the optimal capacities of all system elements

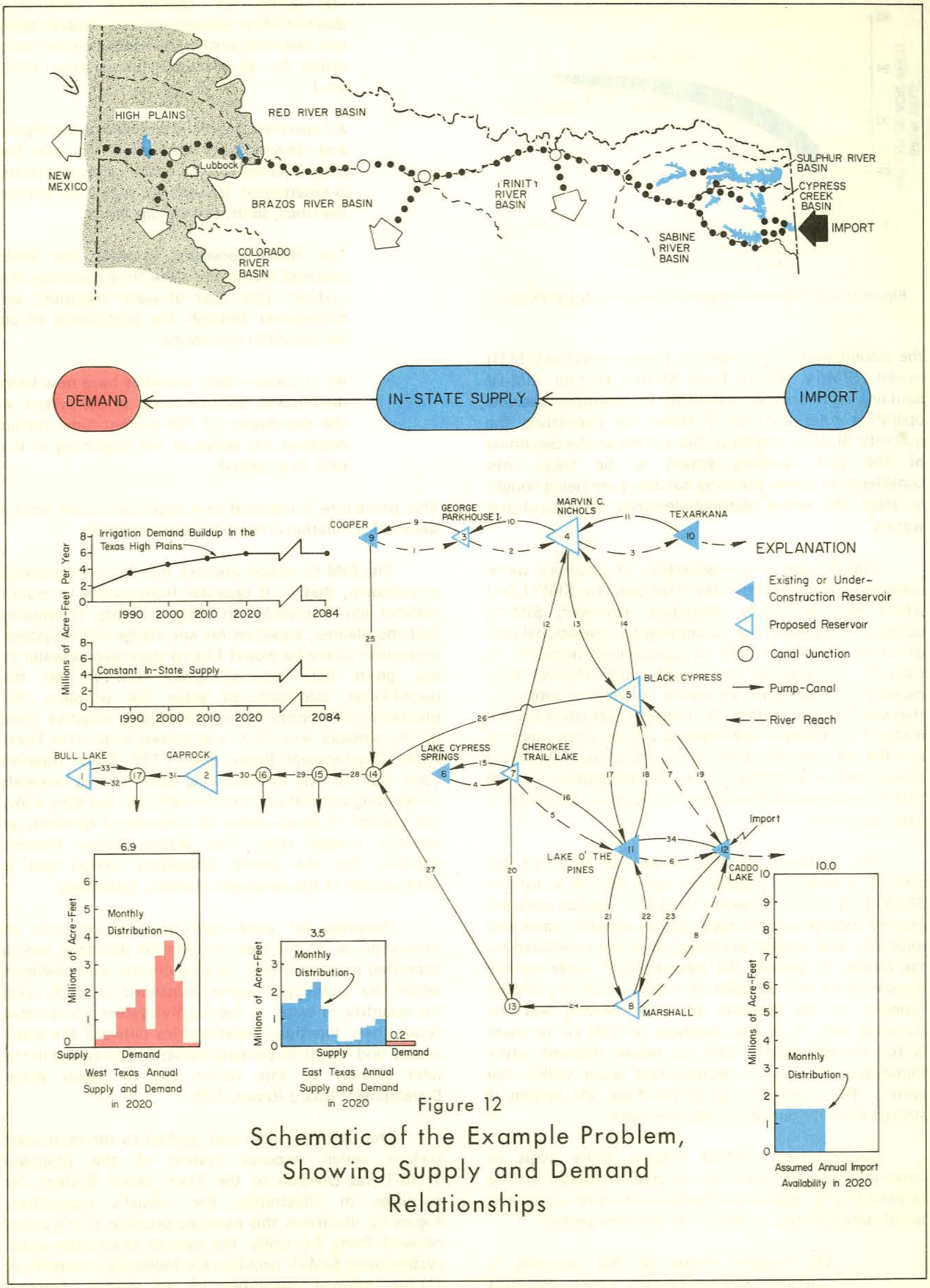


Figure 12

Schematic of the Example Problem, Showing Supply and Demand Relationships (reservoirs, canals); (2) the optimal operation of this system to minimize costs and water deficits; and (3) the capital and operation and maintenance costs for each element for the period of analysis and the hydrologic and demand sequence used. The solution is a function of the hydrologic sequence used. Thus, in order to select a plan which would be expected to more nearly approximate an optimal solution it is necessary to analyze the response of the proposed (or existing) system using a number of different hydrologic sequences. The reason for analyzing multiple hydrologic sequences is that major droughts (or floods), varying in magnitude and duration, may occur at varying points in time within different hydrologic sequences. Since most large systems are designed to be staged with time and the demands are steadily increasing during the system construction-staging period, the temporal location of droughts in the hydrologic sequence determines the size of the water deficits experienced. Obviously, this has a significant effect on the benefits of the water system and should be analyzed in detail. The development of these hydrologic sequences and the choice of sequence to be used in the analysis is an important part of surface water resources analysis. The hydrologic sequence development will be discussed in a following section of this report.

The limitations of SIM-IV are those described at the end of this section. The results of an illustrative analysis using this model are described in more detail in a subsequent chapter of this report.

AL-III

The allocation model, AL-III, is designed to analyze a multibasin water resource system to find:

- the minimum-cost operating plan for a system of reservoirs, canal junctions, canals, and river reaches;
- minimum-cost canal sizes; and
- reservoir operating rule coefficients for use in the SIM-IV model.

The AL-III model is essentially identical to the SIM-IV model in terms of the spatial representation of the water resource system and the use of the network flow solution technique. However, it is different in one important respect—the spatial representation is expanded to include time. The temporal dimension permits an optimal allocation of water based on the assumption that the planner has knowledge of the demands and available supplies in future time periods. This "look-ahead" feature allows maximum storage of water during wet periods so that it is available at the beginning of a drought.

For each time period in the problems, there is a corresponding node-link representation. The representations are connected by the rates at which reservoir storage contents are carried forward in time. These connections are referred to as "storage arcs" (arcs refer to all node connections in the problem, including canal and river links). Thus, the time-space representation of the problem can be envisioned as a layered network, each layer representing a time period with storage arcs connecting the layers. The example system illustrated in Figure 13, expanded to include four time periods, is shown in Figure 14.

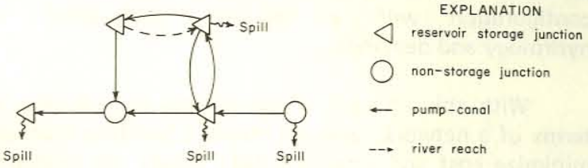


Figure 13.—Spatial Representation of the System Configuration

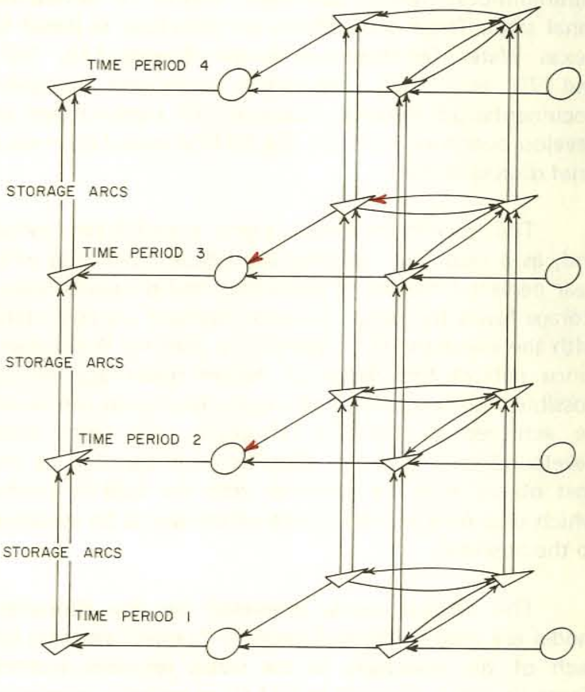


Figure 14.—Spatial Representation of the System Configuration Expanded to Include Four Time Periods

The network thus established is solved, in the conventional manner, using the out-of-kilter algorithm. If monthly time increments are used and the problem contains a large number of nodes and links, the computer storage requirements are large. When this occurs, the allocation model can span only a few years at one time, in which case the number of years spanned is the number of years used in the network. Assuming the total problem involves a ten-year period and the maximum number of years the network can span is four, the procedure works as follows. The first problem solved would involve only the first four years of the total ten-year period, and would produce a solution for the first year. The first year is then deleted from the network and the fifth year added. A solution for the second year is obtained by solving this problem at which time the second year is deleted and the sixth year is added. This process of finding a solution for the first year of the series, removing that year from the series and adding the next year to the end of the series is repeated until the network problem formed by the last four years of the ten years has been solved. This example thus permits optimizing the system operation and configuration with a four-year "look-ahead" at hydrology and demands.

With this concept of structuring the problem in terms of a network, one can obtain a solution that will minimize cost and simultaneously satisfy the inputs to and demands from the system.

The allocation model can be used to obtain reservoir operating rules for SIM-IV, to determine the minimum-cost system operation, and/or to determine canal sizes. These applications are described in detail in Texas Water Development Board Reports 118, 131, and 179 and their supporting computer program documentation volumes. However, the method used to develop operating rules for the SIM-IV model deserves a brief discussion here.

The allocation model spans a multiyear period and, as a result, it simulates the system operation with near perfect foresight of hydrology and demands. Thus, storage levels that result for each reservoir are consistent with the minimum-cost operational plan for the system. Since perfect knowledge of future hydrology is not possible, this minimum-cost operational plan can never be achieved in practice. However, the total costs developed with such an allocation can be used as the cost objective to be achieved with the SIM-IV model which uses only monthly data which would be available to the operator.

The storage levels predicted by the allocation model are used to develop monthly "target" storages for each of the reservoirs in the water resource system. These "targets" are used in SIM-IV as monthly operating rules which tend to minimize spillage of water from the system and maximize the quantity of demands which can be met.

The time history of storage levels in each reservoir, as produced by AL-III, is used to develop storage plots for years in which surplus water was spilled from the system and for years in which deficits were incurred. If the reservoir storage could be maintained along the envelope of *maximum* storage levels that occurred during years of deficits, demands would have a high probability of being satisfied. In other words, this envelope describes a reservoir operational pattern that would minimize deficits. The envelope of *minimum* storage levels that occurred during years of system spillage describes the lowest 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 spillage.

Where the targets are set between these two envelopes depends upon the inflows to and demands from the reservoirs 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 deficits being incurred. The goal, of course, is to find targets that, when used in SIM-IV, will predict the same deficits and spills that were predicted by the allocation model. (It is possible that deficits could be reduced because SIM-IV predicts evaporation losses more accurately than the allocation model.)

In addition to providing information for setting 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. 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 targets should be set very carefully. If the condition occurs where the minimum storage envelope for spillage exceeds the maximum storage envelope for deficits, this means the reservoir is critical but that targets can be set anywhere within the range.

From the two envelopes 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 deficits. 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 about midway between the two envelopes with a smooth seasonal pattern.

Use of the AL-III model to obtain operating rules for the SIM-IV model must be made within the constraints of the following assumptions used in the development of the model:

- Evaporation losses are estimated for all reservoirs for all time periods. These losses are approximated by the product of the monthly evaporation rate and the monthly average reservoir surface area.
- The maximum amount of water available for import is known. Imported water has a constant unit price and can enter the system

at only one node; however, this can be any node in the physical system.

- Maximum demands for water are known.
- Deficits at demand points are allowable and have a penalty cost associated with them.
- Unregulated inflows into reservoirs are known.
- Reservoir storage contents can vary between zero and maximum capacity.
- Spills will occur from the system when the system is completely full or when the cost to transfer water out of the reservoir to the demand point is greater than the cost to spill it.
- The initial storage contents of all reservoirs is known.
- All links have a maximum capacity that cannot be exceeded.
- The unit cost of pumping is the product of monthly power cost per unit of flow per foot of lift and number of feet of lift. These parameters are under input control.

A major limitation on the use of AL-III is in the technique used to estimate reservoir evaporation and the assumption that the quantity of water demanded from the system is fixed. Because of these limitations, SIM-IV must be used as a complementary tool with AL-III for final refinement of a particular system plan.

Research Assumptions, Constraints, and System Operating Rules

Modeling is the process of approximating the prototype for the purpose of evaluating its performance. Because prototypes are more complex than models can ever be, certain simplifying assumptions must be made in order to provide a practical and cost effective analytic capability. The assumptions, constraints, and operating rules used in the development of the simulation and optimization models in this particular research effort include the following:

- Only surface waters are to be modeled. That is, water quality constituents and ground water are not considered.
- The physical system can be represented by a set of interconnected nodes and links. Links correspond to river reaches and pump-canals, while nodes represent reservoir and link junction points.
- Initial storage contents of each reservoir is known.
- Both minimum and maximum flow and storage capacities can be specified separately for canal and reservoir units.
- Staging of facilities will be input at increments of ten years in the general analysis except for seasonal demands and monthly hydrologic data. Demands for water, reservoir inflow quantities, and evaporation rates may be varied on a monthly basis to permit accounting for a demand buildup, a runoff depletion, and stochastic variability in all of these quantities (not applicable to the SIMYLD-II model).
- Monthly time increments are used in simulating the system; thus, operation of canals and reservoirs for routine flood waves is not considered.
- All demands for and inputs of water are to be specified except for the case of import waters where the maximum available will be specified. Thus, runoff, evaporation, system losses, and demands for water are forced upon the system, but import water is drawn upon only when needed. The model SIM-IV permits the irrigation demands to vary with the available supply.
- Import can occur at any one storage or non-storage junction in the system during any limited part of the year up to the maximum monthly availability that is specified.
- The network configuration of reservoirs, pump-canals, and river reaches may be interconnected in any possible manner.
- Spills out of the system are, by definition, the most expensive alternative use of water. Therefore, spills will occur only as a last resort. However, the SIMYLD-II model permits varying the value of spilling relative to the other uses of water.
- 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.
- All demands for water and runoff quantities occur at nodes and reservoirs, respectively.

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

- 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.

- Those reservoirs with adequate capacity for receiving import water may be specified as a means to control the quantity of water imported and the location of its interim storage.

- Lower constraints can be set on demand arcs 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.

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

- Water data are entered in units of 1,000 acre-feet, and after computations have been made the results are rounded to the nearest 1,000 acre-feet and reported by computer print-out.

- Only storage allocated for "conservation" purposes can be used for reregualtion.

- The ditch size at the last year of the simulation period can be larger than the actual pump-capacity of the canal.

- Two options are available upon which to optimize monthly internodal water transfers. One uses unit pumping costs; the other uses unit pumping costs plus prorated capital costs to calculate total unit cost to pump (Not applicable to SIMYLD-II).

- The problem case is to be calculated as having a 100-year economic life and a maximum of a 36-year simulation period.[1]

- A minimum-cost objective is to be used in conjunction with penalty costs for failure to meet demands.

- Because an economic objective criterion is specified, a specified economic value for meeting demands versus the economic value of spilling water of storing water is required. Therefore, it is assumed that demands for water will be met only if the value for meeting demands is greater than the penalty for meeting them.

- Unit penalty costs for incurred shortages are a model input and can be varied by node by season, whereas reservoir storage preferences can be varied by reservoir by season.

- Canal costs are considered as two components—that component which cannot be staged (e.g., ditch and right-of-way costs) and that component which can be staged (e.g., pump, motor, and housing costs). For facilities a percentage penalty cost for capital expansion may be imposed. (Not applicable to the SIMYLD-II model.)

Simulation of Ground Water

As noted, the underlying assumptions for development of previously described models included their consideration of surface water alone. Because of the significiance of ground water in Texas, specialized ground-water models have been developed for use in the Board's water planning. The objective of the Board's ground-water studies is to determine the availability and yield capacity of the large aquifers of the State at a level of refinement adequate to support development and management of these resources in conjunction with surface water supplies. To meet this goal, the Board has applied a finite-difference model to simulate the hydraulic behavior of confined and unconfined aquifers. The model, originally developed by the U.S. Geological Survey (Pinder and Bredehoft, 1968), has been extensively modified by the Board.

The finite difference model has the capability of simulating water table elevations or piezometric levels under varying recharge and pumping patterns. In order to simulate the hydraulic behavior of a ground-water basin with this model, the basin must be represented by a grid of square or rectangular elements. Once the basin elements have been selected, the computer program calculates the water table elevation (or piezometric head) in each element and all flows between for each time period simulated. Normal practice indicates that computational intervals of 1 year or less and total simulation periods of 5 to 10 years are satisfactory to verify the accuracy of the model. The Board has acquired a similar but more flexible model from the Illinois State Water Survey (Prickett and Lonnquist, 1971). This model is being used to replace the U.S. Geological Survey model on new investigations. Both computer programs require three basic types of input data:

---

[1] Thirty-six years was the length of the staging period for the proposed Texas Water System (1985-2020).

Geometric Data

- coordinates for the center of each element

Aquifer Characteristics Data

- permeability of each element
- specified yield (or storage coefficient) of each element
- elevation of the bottom and top of the water-bearing sediments in each element

Hydrologic Data

- initial water table elevations in each element
- pumpage from each element for each time period
- recharge rates into each element for each time period

Verification of the ground-water simulation model involves assembling historical information on pumpage, recharge, springflows, and water surface elevations and using these data to simulate the historical water level changes in the aquifer. Aquifer water levels are used as the indicator of simulation verification and when all nodes of the model are within the user-selected error criterion, the model is considered to be verified. This is often a long and laborious procedure and involves continued adjustment of permeabilities and storage coefficients to obtain matching simulated and historical aquifer water levels. Once a model of the basin has been developed and verified, the first two data types are constant. The recharge and pumpage, on the other hand, will vary from time period to time period in the simulation.

The Board is currently completing a simulation model study of the Carrizo-Wilcox aquifer in South Texas using the modified U.S. Geological Survey model. This study evaluates the response of future water levels to alternative projected rates of pumping. The model results are used to recommend future pumping practices to conserve the important ground-water resource. Figure 15 shows, based on simulation results, the areas most favorable for development in the Carrizo-Wilcox aquifer. Work has recently been initiated in applying the Illinois model to the Edwards Limestone aquifer. Location and extent of these aquifers the Board is modeling are shown on Figure 16.

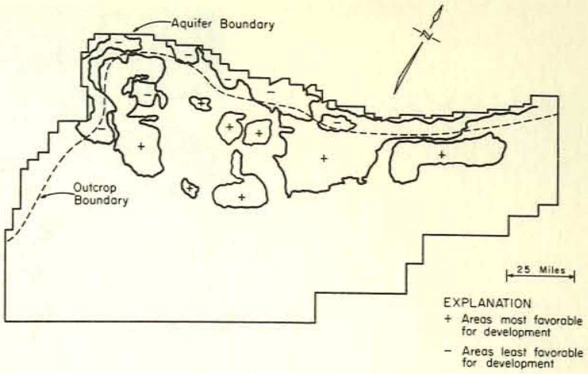


Figure 15.—Example of Ground-Water Model Output, Showing Areas Most and Least Favorable for Well Field Development

Simulation of Demand for Water by Agriculture

The demand for water by agriculture in a large area with several crops and soil types can be modeled as a two-level system. The basic building block is the simulation of the demand for water by a particular crop on a particular soil type in response to climatological-meterological factors. The water that a crop uses is extracted from the ground on which it grows. The porosity of the soil dictates the maximum amount of soil moisture the ground can hold. The depth from which the crop can extract this water is limited by the root depth. The amount of water required by the crop for evapotranspiration is related to pan evaporation. Rainfall and irrigation applications provide the soil moisture which is required by the plant. The Board has developed and uses two different irrigation models.

DEMAND-II

In the model DEMAND-II the assumption is made that the soil moisture is augmented to saturation by irrigation whenever it drops below 50 percent of capacity. Therefore, for a given sequence of monthly values of rainfall and evaporation, the model identifies in which months irrigation is required and how much water is to be applied per acre of each crop. These sequences of rainfall and evaporation can either be those observed historically or those that have been synthetically (stochastically) generated. The resulting sequence of irrigation demands per acre for each crop and soil combination must, at a higher level, be multiplied by the corresponding acreage of each combination and then aggregated to obtain a sequence of irrigation water demands for a large area.

The data required for the DEMAND-II irrigation model can be grouped into two general categories:

Hydrologic Data

- monthly total values for rainfall and evaporation over the simulation period (A modified verison of DEMAND-II

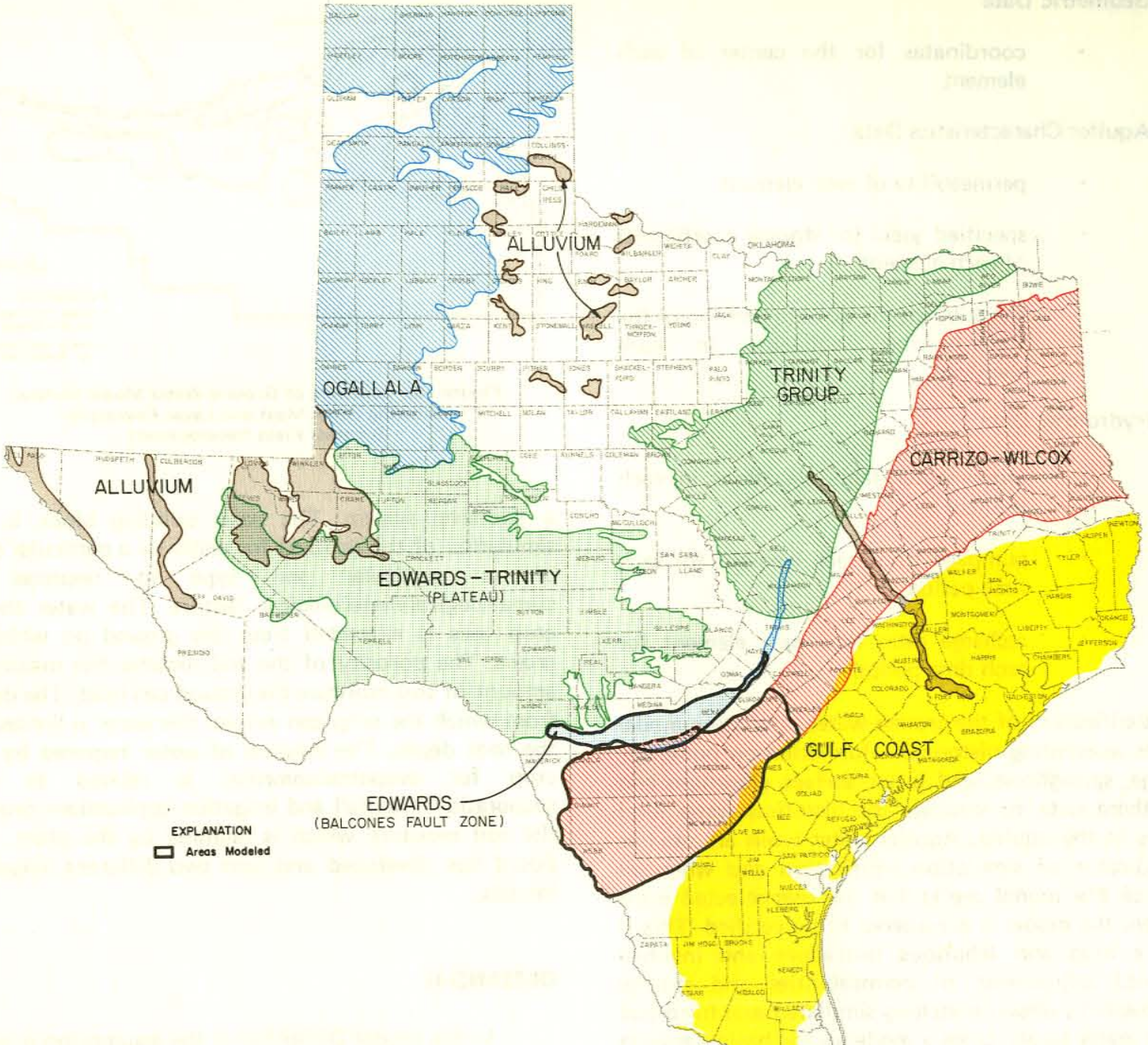


Figure 16.—Major Aquifers and Areas Modeled

can operate on semi-monthly time intervals.)

- a coefficient relating the amount of rainfall to that which can be infiltrated into the soil before it runs off (when the soil is not already saturated)

Agricultural Data

- porosity of each soil type
- root zone depth of each crop in each soil
- the number of acres of each crop-soil combination
- a monthly consumptive use coefficient for each crop that relates evaporation to the amount of water a plant uses through evapotranspiration
- a consumptive use coefficient for fallow periods
- an efficiency factor that reflects the transmission losses in the irrigation supply system

Figure 17 shows the results of DEMAND-II in an example of the projected increases in irrigated acreage in the High Plains and north-central Texas regions as described in the Texas Water Plan for the period 1985 to 2020. Because of the extreme variability of rainfall and

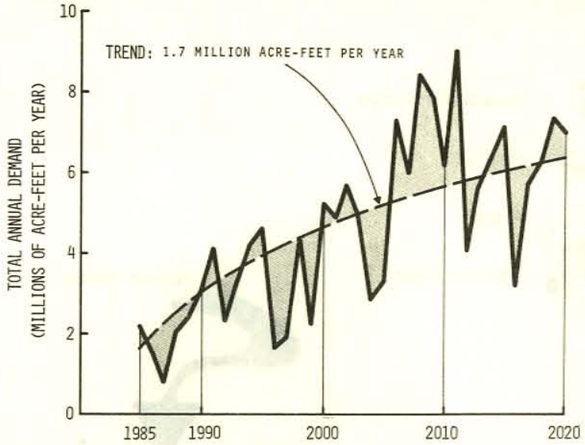


Figure 17.—Example of Yearly Response of the Irrigation Macro-Model

evaporation (historically or synthetically generated), the demand curve fluctuates widely about a trend established by the expanding acreage served.

Figure 18 shows the monthly demand for a typical acre over a 3-year period. Note that the irrigation demand is strongly influenced by the difference in rainfall and evaporation. These sequences of irrigation demands, whether the result of historical or stochastically generated data, can be used with the supply system simulation models to evaluate the risks associated with various designs.

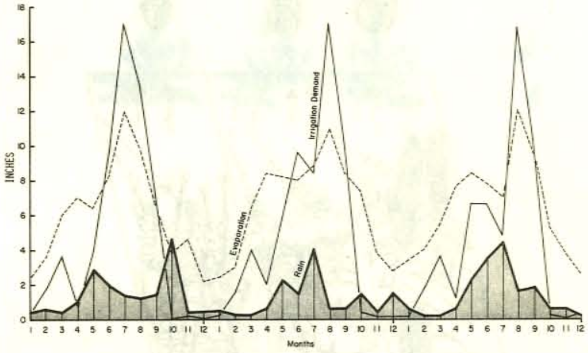


Figure 18.—Typical Monthly Response of the Irrigation Macro-Model

Interactive Demand-Supply Simulation

Another, more comprehensive method of simulating irrigation demands has been developed which permits the quantity of water demanded to be related to the available water supply. This modeling technique, termed dynamic economic simulation (DES), additionally provides a time stream of revenues to agriculture resulting from a sequence of water supply inputs from the SIM-IV model. Because it takes into account the uncertainty of future meteorologic conditions as it selects rational planting and irrigation tactics for the farmers it simulates, DES can be used as a planning tool as well as an operating simulation model. The spatial setting for this analysis is shown in Figure 19. The water that is available to the entire area is a result of inflow to the storage system plus any amount imported from external sources minus any spills.

It is assumed for this model that farmers act rationally but independently to maximize their expected monetary return from their entire farming enterprise. This involves making several types of allocations. The first one entails the allocation of planting time of his available land to his crops within the constraints placed upon him by government programs. This decision is also affected by the amount of water the farmer expects to have available to him to apply to these crops throughout the remainder of the growing season. For example, if, in a particular year, the amount of available water is predicted to be high, the farmer will rationally plant a complement of high yield but high water use crops. Conversely, if the water available is predicted to be low in a particular year, the farmer will choose crops which use less water and may increase the number of acres he farms dryland (without irrigation). Once the farmer has made the decision of which crops to plant in the springtime, he is somewhat committed and, for the remainder of the growing season, tries to allocate the available water among the various competing crops he has planted to maximize his aggregated net return. However, he does have the flexibility to adapt his irrigation decisions in the face of fluctuating meteorological conditions as they become known.

The water supplier, generally some public agency, is charged with the responsibility of enhancing the well-being of the citizens affected by water resources projects. In this model it is assumed that the supplier of water in an area allocates the water available, after higher priority municipal and industrial needs are met, among the farms in an area in a manner that maximizes expected returns to the entire area. Other interfarm allocation patterns determined by vested rights are less general and therefore could also be considered.

The context in which the physical representation of a crop's use of soil moisture is presented in DES is an extension of the concepts of DEMAND-II. Its reality is augmented by the consideration of the health status of a crop and the consequences on final yield of adversely affecting this status through failure to maintain sufficient soil moisture to insure optimal plant growth and maturity. Additionally, the costs associated with planting, harvesting, cultural operations, and irrigation are considered as well as the returns realized at the end of the growing season.

A dynamic programming formulation is used in a model which optimally times the application of any

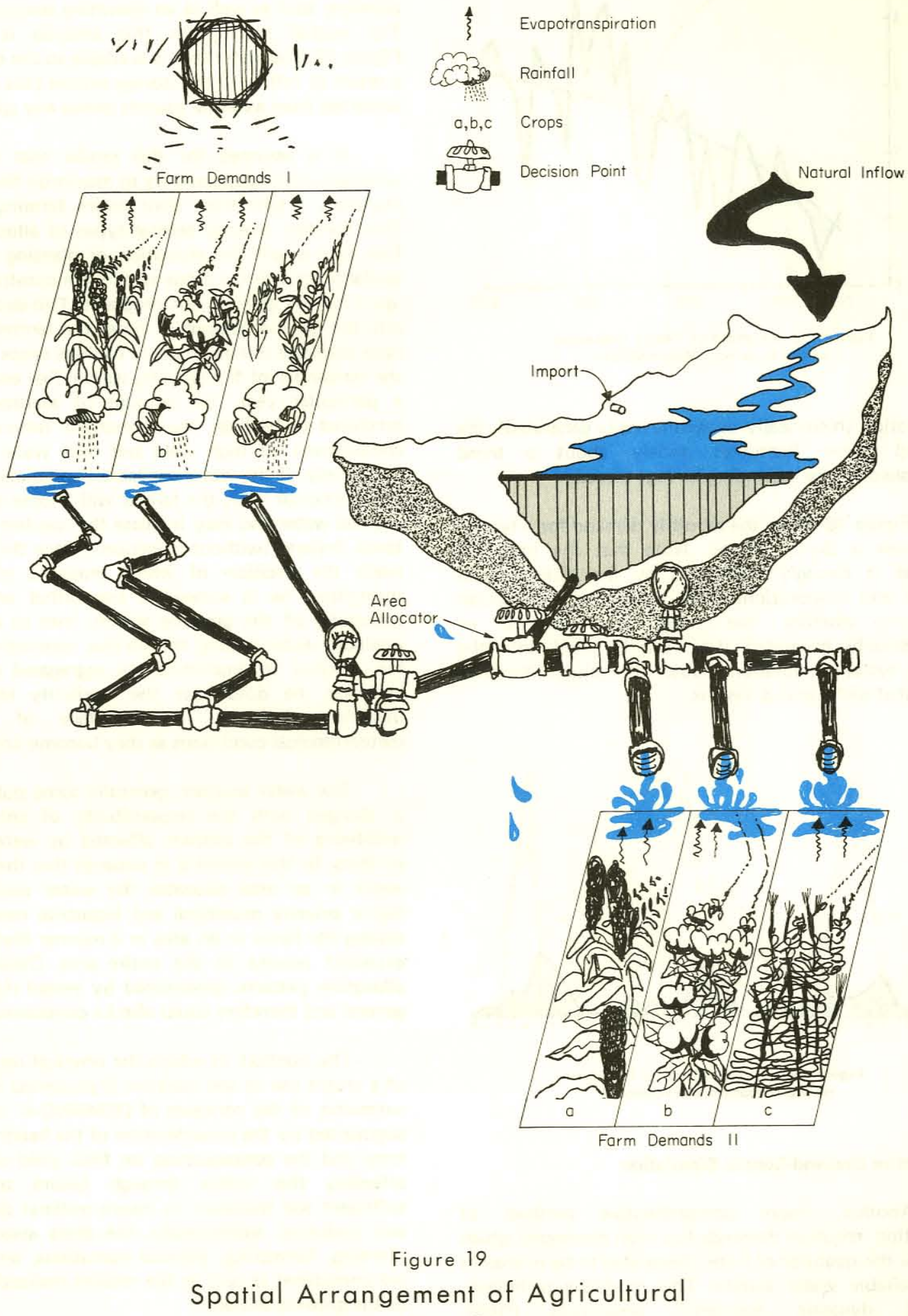


Figure 19

Spatial Arrangement of Agricultural Water Use System given amount of water over the remainder of a specific growing season under stochastic hydrologic conditions for each crop. From the output of this analysis it is possible to determine the worth of allocating different amounts of water to each crop for any time period based on the soil moisture and health status of each crop. This information is also needed for use in a linear programming model which determines the optimal cropping pattern based on a given estimate of water availability. These time-consuming optimizations are performed prior to the simulation, with the results stored on magnetic disk for easy access during the simulation. This feature makes the simulation extremely fast and efficient while it considers many factors.

The simulation of the irrigation system is described as "dynamic" because it reflects the farmer's adaptive decisions on planting patterns and subsequent irrigations which are made on the basis of his information on the current conditions of his crop and projections of water availability. The main aspects of the simulation can be sketched in the flow chart shown in Figure 20.

The data required for this analysis include, in addition to the information required by the other demand model, the following:

- yield-soil moisture relationships for each crop for monthly time periods in the growing season
- gross revenue as a function of yield for each crop

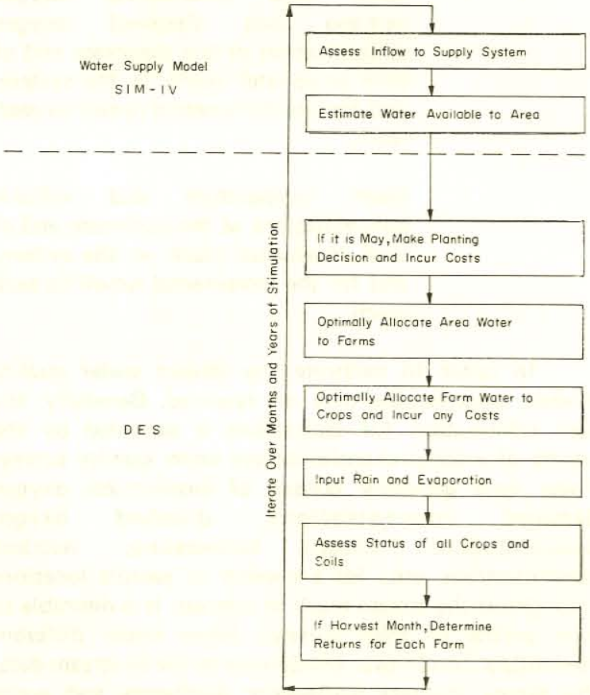


Figure 20.—Flow Chart, Interactive Demand-Supply Simulation for Irrigated Agriculture

- the costs of planting, irrigation, cultivation, and harvesting for each crop
- acreage of each farm being simulated
- government restrictions, if any, on acreage for a given crop
- government payments, if any, for each crop
- planting and harvest months for each crop

The model DES calculates and, with the specification of the correct print option, can print the following items for every month of the simulation:

- the soil moisture status beneath all crops being grown on each farm
- the health status of all crops being grown on each farm
- the decision of how much to irrigate each crop in a manner which maximizes expected returns to each farm
- the cost incurred for each crop for any cultural operations, planting, irrigating, or harvesting
- the culmulative cash position of each farm
- if it is a planting month, what the planting pattern is for each farm
- if it is a harvest month, what the net income is for the growing year for each crop.

The output provides information that yields insight into the interactions of a water supply/demand system. The basic limitations of the modeling technique are:

- It does not explicitly consider the capacity of the irrigation system, so that in some cases more water might be demanded than could be supplied
- It is difficult to vary prices of water or cultural operations during the planning period without having to solve an extremely large number of problems
- It assumes each farmer's objective is to maximize net farm income.

The DES technique can be applied to a ground water supply system, a surface water supply system, or it can be used to evaluate alternative water allocation policies. It might also be used to provide insight into the farm income and market supply effects of alternative pricing policies and crop allocation programs.

Environmental Simulation

Stream and Reservoir Water Quality

Water quality considerations are extremely broad and varied in any proposed water development project, and the problems associated with the effects of municipal, industrial, and agricultural wastes are of major importance. Thus, the simulation of water quality conditions within a stream or reservoir under existing and projected river basin development is an essential analysis for comprehensive water resources development planning.

This need has led the Board to develop a set of computer programs to simulate the distribution of several water quality parameters within streams and reservoirs. A Streeter-Phelps stream quality model (DOSAG-I) is the model used for the initial screening of alternatives to select those warranting more detained analysis. This model calculates mean monthly biochemical and nitrogenous oxygen demands and dissolved oxygen in a typical stream system such as the one shown in Figure 21.

The Board has developed a finite difference stream quality model, QUAL-I, a more comprehensive program than the Streeter-Phelps model, which is comprised of three interrelated quality routing models. Collectively they produce an hourly simulation of stream temperature, carbonaceous and nitrogenous biochemical oxygen demand, and dissolved oxygen. Concurrently, this model can simultaneously route as many as three conservative minerals within a system of streams as shown in Figure 21, and can handle multiple waste inputs, withdrawals, and incremental runoff. Additionally, both the Streeter-Phelps model and the finite-difference model have the capability of calculating waste treatment levels and/or flow augmentation requirements necessary to maintain a specified minimum dissolved oxygen concentration at any point in the system.

The typical data required for the stream water quality models include:

Geometric-Hydraulic Data

- number of tributaries of the river basin mainstem and length of each
- length of the river reaches between points of tributary inflow
- velocity-discharge and depth-discharge relationships for each tributary and for the mainstem
- mean flow in the headwater reach of each tributary during the period of simulation
- Manning's roughness coefficient for each reach

Data for Stream Temperature Simulation

- latitude, longitude, standard meridian, and mean elevation of the basin
- coefficients relating surface evaporation to windspeed
- cloudiness, wet and dry bulb temperatures, barometric pressure, and windspeed

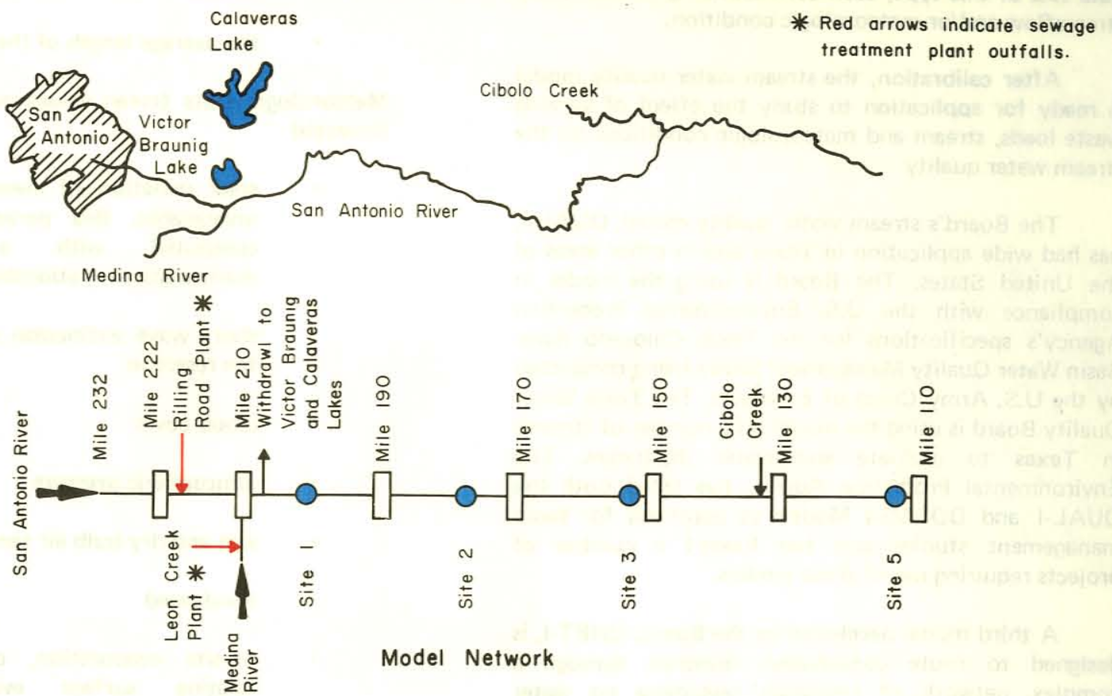
Inflow-Outflow

- temperature and mineral concentrations of waste loads to the system
- location, mean flow, and total biochemical oxygen demand of waste loads to the system
- location and mean flow of withdrawals (if any) from the system

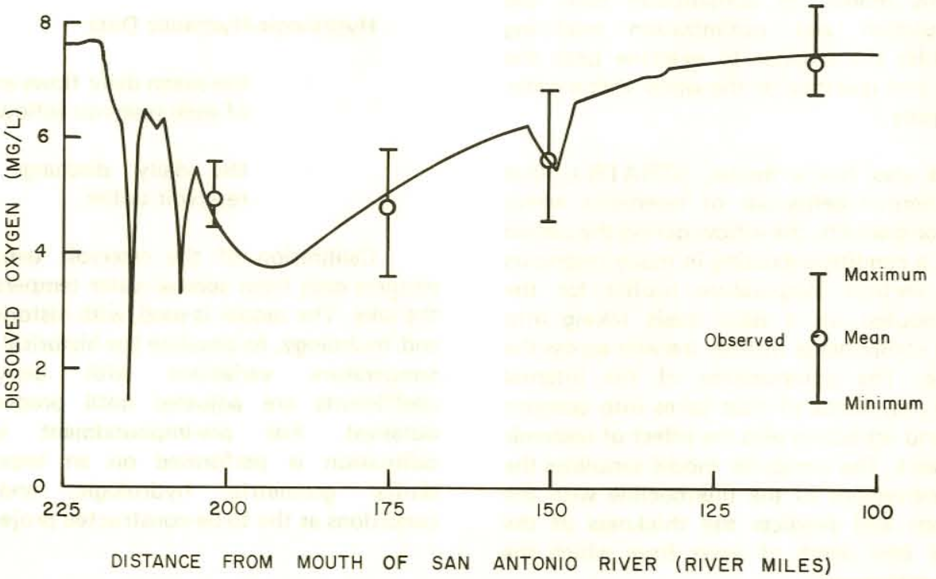
Chemical-Biochemical Data

- mean total biochemical oxygen demand and dissolved oxygen concentration at the upstream end of each headwater reach in the system, and for the incremental runoff to each reach
- mean temperature and mineral concentrations at the upstream end of each headwater reach in the system, and for the incremental runoff to each reach.

In order to calibrate the stream water quality models, considerable data are required. Generally, the best information for calibration is provided by the results of a comprehensive stream water quality survey. These data generally consist of biochemical oxygen demand concentrations, dissolved oxygen concentrations, stream temperature, nutrient concentrations, etc., for a number of sample locations throughout the stream reach of interest. It is desirable to have several of these surveys, taken under different streamflow conditions. In addition to the in-stream data, the survey involves wastewater discharges and water withdrawals, and their water qualities. These latter data are then used as input to the stream quality model, and the model is then calibrated to reproduce the data



Model Network



Simulation Results

Figure 21
Typical Stream Water Quality Model Network and Simulation Results

measured in the stream. It is desirable to have several data sets of this type, each corresponding to a different streamflow and/or meteorologic condition.

After calibration, the stream water quality model is ready for application to study the effect of varying waste loads, stream and meteorologic conditions on the stream water quality.

The Board's stream water quality model, QUAL-I, has had wide application in Texas and in other areas of the United States. The Board is using the model in compliance with the U.S. Environmental Protection Agency's specifications for the Texas Colorado River Basin Water Quality Management Study being conducted by the U.S. Army Corps of Engineers. The Texas Water Quality Board is using the model on a number of streams in Texas to evaluate wastewater discharges. The Environmental Protection Agency has listed both the QUAL-I and DOSAG-I Models as approved for basin management studies and has funded a number of projects requiring use of these models.

A third model developed by the Board, QNET-I, is designed to route conservative minerals through a complex network of reservoirs (assuming no water quality stratification exists), canals, and river reaches. The use of this model, in conjunction with the hydrologic simulation and optimization modeling capabilities, enables the planner to examine both the probable quality and quantity of the water that a water system would supply.

The Board also has a model, STRATR-I, that simulates the thermal behaviour of reservoirs where storage is large compared to the inflow during the period of stratification, a condition existing in many reservoirs in Texas. The vertical temperature profile for the reservoir is computed on a daily basis taking into consideration all components of heat transfer across the reservoir surface. The computation of the internal distribution and movement of heat takes into account vertical mixing and advection plus the effect of reservoir inflows and releases. The computer model simulates the formation and movement of the thermocline with the change in seasons and predicts the thickness of the withdrawal layer (the depth of water from which the water is actually withdrawn).

The hydrologic-meterologic data base required to apply the model, while rather broad, is generally not difficult to acquire. The minimum data set is specified as follows:

Physical Data

- latitude, longitude, standard meridian, and elevation of the reservoir site
- area-capacity data for the reservoir
- the number and elevation of the outlets
- the average length of the reservoir pool

Meteorologic Data (mean values over daily intervals)

- solar radiation (if measured data are unavailable, this parameter can be computed with a theoretical mathematical relationship)
- short wave extinction coefficient for the reservoir
- cloud cover
- atmospheric pressure
- wet and dry bulb air temperatures
- windspeed
- on-site evaporation, or coefficients relating surface evaporation to windspeed

Hydrologic-Hydraulic Data

- the mean daily flows and temperatures of each reservoir inflow
- the daily discharge through each reservoir outlet.

Calibration of the reservoir temperature model requires data from several water temperature surveys of the lake. The model is used, with historical meteorology and hydrology, to simulate the historical record of water temperature variations with depth. Dispersion coefficients are adjusted until proper simulation is obtained. For pre-impoundment studies, model calibration is performed on an impoundment with similar geometric, hydrologic, and meteorologic conditions as the to-be-constructed project.

Estuarine Tidal Hydrodynamic and Water Quality Models

In Texas, the long Gulf Coast shoreline with its several bays and estuaries presents a major planning consideration, relating as it does both to a complex estuarine system and the river inflows from the river systems. Management of the estuarine systems requires an understanding of tidal hydrodynamics and salinity transport processes within each estuary. As a planning aid, therefore, the Board has developed, with consulting assistance, a mathematical hydrodynamic model, a mass transport model, and their attendant usage procedures. These models are designed to determine the effects of alternate estuarial development and management plans on circulation and tidal patterns in shallow, irregular, non-stratified estuaries such as the San Antonio Bay complex shown in Figure 22. The tidal hydrodynamic model, HYD-I, computes the temporal and spatial distribution of velocities and water surface elevations at each nodal point of a computational grid that is superimposed on an estuary. The estuarial properties along any given vertical line in the estuary are assumed to be homogeneous, i.e., complete mixing.

The HYD-I model takes into account bottom friction, submerged reefs, overflow over low-lying barrier islands, fresh water inflow (runoff), other inflows, ocean tides, wind, rainfall, and evaporation. The model is used to study intra-tidal behavior, changes in scour and sedimentation patterns produced by estuarial development, and to evaluate the dispersion characteristics of waste outfalls. The primary output from the tidal hydrodynamic model is a time-history of water elevations and velocity patterns over the estuary. These data may be stored on magnetic tape for later use in describing the advection terms of the estuary water quality-ecological models.

One of the more important indicators of the conditions of an estuary is the concentration and variability of salinity. As development proceeds in a river basin and its estuary, the natural fresh water inflows to the estuary generally decrease and, more importantly, their seasonal distribution is altered. The result may be a progressive increase in salinity, seasonal periods of higher than "normal" salinity, and possibly an alteration of the existing ecosystem of the estuary.

The Board's estuary mass transport model, SAL-I, can be used to analyze the distribution of salinity in shallow, non-stratified, irregular estuaries for various tidal and fresh water inflow conditions. The model is dynamic and takes into account location, magnitude, and quality of fresh water inflows; location and magnitude of withdrawals; evaporation and rainfall; and advective transport and dispersion within the estuary. The primary outputs from this model, as illustrated in Figure 22, are the tidal-averaged salinity concentrations at each nodal point of the computation grid used by the hydrodynamics model. In addition to analyzing salinity changes in the estuary due to increased withdrawals and/or decreased fresh water inflows, the model can be used to evaluate the effects on the salinity distribution of intra-estuarial development projects, such as dredging and filling operations, that alter the circulation pattern within the estuary. In addition to salinity, the model can be used to simulate the transport of any other dissolved conservative material or material which can be assumed to be a conservative within an estuary. Thus the transport materials such as mercury, certain pesticides, etc., through an estuary can be evaluated.

The following data comprise the basic set for applying the estuary hydrodynamics model. Time varying data must be supplied for hourly intervals.

Physical Data

- topographic description of the estuary bottom, tidal passes, etc.
- location of inflows (rivers, wastewater discharges, etc.)

Hydrologic-Hydraulic Data

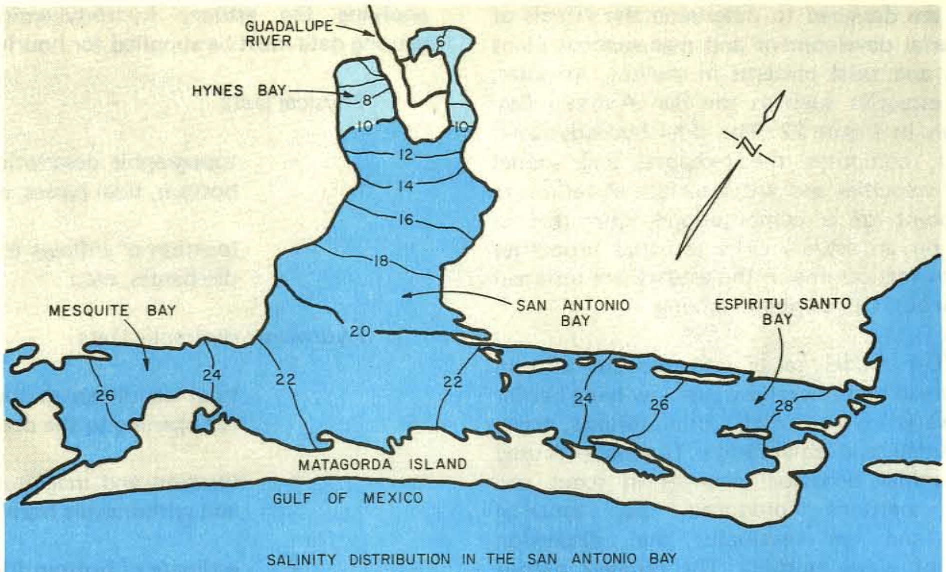
- tidal condition at the estuary mouth (or opening to the ocean)
- location and magnitude of all inflows and withdrawals from the estuary
- estimate of bottom friction
- wind direction and speed (optional)
- rainfall history (optional)
- site evaporation or coefficients relating surface evaporation to windspeed.

The basic data set required to operate the estuary salinity simulation model is a time history of tidal-averaged velocity patterns, i.e., the output from the estuary hydrodynamics model. In addition, a time-history of the salinity concentrations of all inflows to the estuary must be provided, and an initial salinity distribution within the area must be specified.

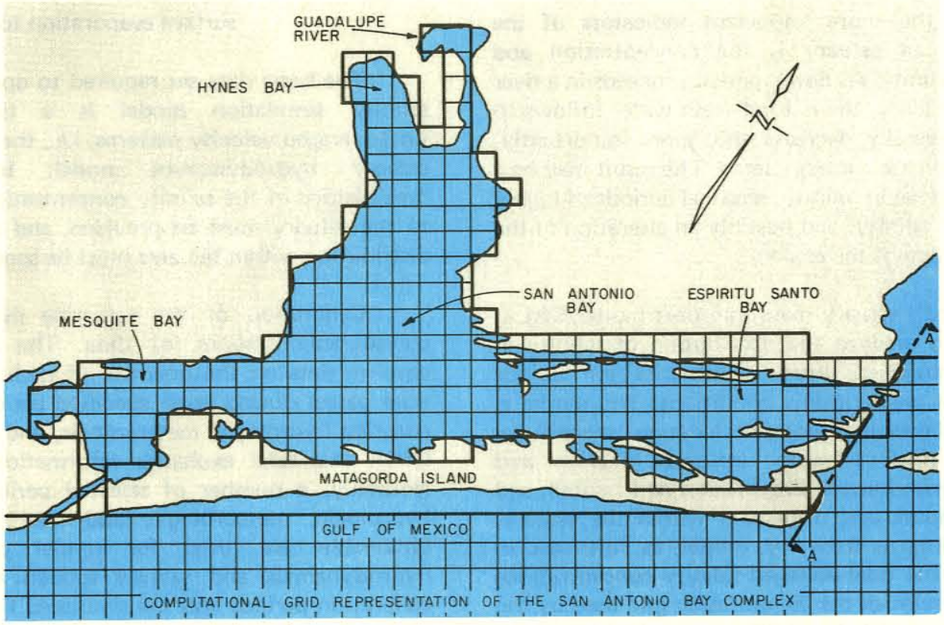
Calibration of the estuarine models requires a considerable amount of data. The best calibration requires data on the quantity of exchange through the tidal passes during some specified period of reasonably constant hydrologic, meteorologic, and tidal conditions. Often this tidal exchange information is unavailable. Normally, a number of selected periods in which all hydrologic, meteorologic, and tidal information are obtainable are used for model calibration. The hydrodynamics and salinity models are run for the calibration periods and the simulated tides and salinities are compared to the measured values. Reef coefficients, bottom roughness, bathymetry, etc., are adjusted until reasonable reproduction of measured data, for all of the historical periods, is obtained. The models are then considered to be calibrated.

Data Base Development

An important early step in the analysis of a water resource planning problem is the development of an adequate data base. Data base development is likely to



SALINITY DISTRIBUTION IN THE SAN ANTONIO BAY COMPLEX, EXAMPLE AT LOW-INFLOW CONDITION
(Salinities in parts per thousand)



COMPUTATIONAL GRID REPRESENTATION OF THE SAN ANTONIO BAY COMPLEX

Figure 22
Estuary Hydrodynamics and Salinity Simulation

be the most arduous phase of the entire planning program. The data which must be available for the planning of a typical surface water supply system includes[2]

- Hydrologic data to estimate the total water resource available in the region of interest, including potential sources of import water. Historical hydrologic records, and frequently synthetic hydrologic records, are required. The techniques developed by the Board involve the use of both types of hydrologic sequences. These hydrologic data include reservoir inflows, return flows, reservoir evaporation rates, and precipitation. Other specialized data which may be required, depending upon the particular situation, are such factors as seepage or percolation losses from reservoirs, transpiration losses, etc.

- Demands for water. These demands must consider current and projected population growth, industrial activity, and food and fiber production. In addition, demands for water-based recreation and environmental protection or enhancement must be considered. Demands should normally include the effects of variable hydrologic conditions. Additionally, alternative projections of population and economic growth should be used to estimate the possible variations in projected demands.

- Reservoir characteristics for each potential or existing reservoir in the supply system, including area-capacity and elevation-capacity relationships, capital and operating cost functions, and information relating to other physical characteristics of each facility such as the number of size of the outlet works, and the reservoir length at maximum pool, minimum pool, sediment storage allocation, etc.

- Characteristics of the river reaches and potential or existing transfer links; e.g., canals, pipelines, etc. Maximum and minimum capacities, seepage and evaporation losses, and capital and operating cost functions for pipelines and canals are the principal data usually required. The cost and sources of energy for system operation are also necessary data.

- System characteristics such as the planning period, the amortization period and discount rates to be used, potential sources of import water, its availability, and cost.

- The availability of alternative water supplies such as ground water, reclaimed wastewater, and desalted ground and/or surface waters. These data may consist of aquifer characteristics, pumping cost, desalting and reclamation costs.

- The quality (chemical and biological) of all potential water supplies and sources in the planning region.

- The economic structure of the planning region. In particular, the relationships of the major water users to other sectors of the economy. In particular, the payment capacity of potential water users must be evaluated.

The data listed above are required for an analysis of the supply-demand portion of the surface water resource planning problem. However, multi-objective planning requires that consideration be given to the economic, environmental, and social effects of water resource development. The addition of these considerations to the planning problem significantly expands the data requirements. These additional data include, but are not limited to, the following:

- The nature of the terrestrial and aquatic environments in the planning region. This includes data on vegetation, fish and wildlife, and current and projected land use. Much data of this type are needed to meet the requirements of the National Environmental Protection Act and these data are more adequately described therein.

- The social characteristics of the area of interest. Data on the recreational opportunities, income, and employment in the region are important in the assessment of the impact of a large-scale, multi-objective water resource development program.

To assist in satisfying the data requirements for the planning of a surface water supply system, several computer-oriented techniques have been adapted and applied during the three-phase research project. Data requirements for the more general planning case are more diverse, and at present, systemized means for satisfying them have not been perfected. The following discussion briefly addresses the techniques used in preparing the data base for analyzing the multibasin surface water allocation and supply system.

Hydrologic Data Refinement Study

The quantity and quality of flow of the principal rivers and their tributaries have been measured at numerous strategically located gages throughout the State for several decades, and extensive manipulations,

---

[2] This list is not intended to be all-inclusive. Many water planning problems will require additional data not listed herein, and some problems may require only a fraction of these data.

adjustments, and statistical analyses of these recorded data have been made for various planning studies and project design.

Streamflow records, however, must be recognized for what they actually represent; that is, the observed flows of streams passing particular locations within the river systems. Streamflow, as measured at a gaging station, in reality has been and is influenced by many of man's activities in most river basins. Construction and operation of reservoirs, stream diversions for various uses, municipal, industrial, and agricultural return flows, exports from and imports into each basin, agricultural land conservation measures, construction of floodwater retarding structures, land use, and ground-water extractions are among some of the most significant factors which have continuously altered hydrologic regimes over time. Such changes will continue in the future. The effects are of significant magnitude in many cases.

The influence of man's activities on the characteristics of a stream's regime at a particular gaging site are commonly not obvious, nor separable from one another, in the recorded streamflow and water quality data. These effects on the quantity and quality of streamflow are generally reflected in the form of trends over a long period of time. Additionally, these long-term trends are commonly masked by short-term hydrologic events.

In order to provide a consistent set of streamflow data for planning purposes the Board initiated a program in 1969 identified as the Hydrologic Data Refinement Study, which had the following major objectives:

- Developing a set of criteria, methodology, and procedures for refining or adjusting the observed historical hydrologic data for Texas streams to steady-state conditions, such as "natural" or unimpaired conditions.
- Applying these criteria, methodology, and streamflow adjustment procedures, using computerized techniques and programs, to all major river basins of the State in order to develop a complete set of hydrologic data, for a common climatic period, for each basin.
- Compiling and storing these refined or adjusted historical data in a readily usable and retrievable form, with the flexibility for continuing modification and updating of the body of data incorporated into the methodology and storage system.
- Using the adjusted historical data base, development of a body of hydrologic data, primarily a sequence or sequences of streamflow and related hydrologic parameters, for various postulated or projected conditions of river basin development, water use, and water management within each basin - based on the presumption that the future regime of precipitation and related meteorologic phenomena will be approximately the same as that experienced in the past.
- Using these sets and sequences of refined hydrologic data, in lieu of the historical recorded data, in the Board's highly advanced study techniques oriented toward solving the critical and complex water supply and demand problems unique to Texas.

The study, for a particular river basin or group of basins, is conducted in five major phases. For the purpose of scheduling and monitoring the progress of this type of study, the "critical path" procedure is used. All basin studies and tasks are diagramatically identified, interfaced, and scheduled as appropriate to insure that necessary information and data are available to the various assigned staff at the proper time.

Phase I consists of data collection, compilation, and where necessary, the "filling in" of missing records within the selected period. Initially, river basin maps are developed which include definitions of hydrographic units, key control points, measurements and computation of drainage areas and river mileage, and application of related data-coding procedures. The location of all projects (reservoirs, etc.), streamflow diversion points, wastewater outfalls, etc. are identified on the maps. Geologic and aquifer maps of the basin are also prepared, areas of ground-water pumpage are defined, and stream reaches within which channel gains or losses are known or believed to be significant are identified.

Emphasis is placed on the collection and compilation of all available historical information on municipal and industrial water use and return flows, meteorogical and climatological data, and reservoir operational data. Data on the number, location, sizes, and dates of construction of farm ponds and local floodwater-retarding structures and measures are also collected, compiled, and analyzed during Phase I. Soil characteristics and soil classification data are assembled. Information on existing and historical trends in land use and land management practices is compiled and analyzed. Agricultural water use and return flow information are also collected, where available, and estimated for periods of missing record.

At the completion of Phase I, all important information and data have been compiled and stored by hydrographic unit. Phases II, III, IV and V require identifying problems unique to each hydrographic unit or basin, developing various statistical methods and correlation techniques for data manipulation, applying the techniques in the streamflow refinement process, and preparation of a report which presents the adjusted flows and information used in the refinement process for the river basin or basins being studied.

The methodology and sequence followed in the various degrees of adjustment of the recorded historical flows and the development of refined flows are shown in Figure 23. Basically, the procedure involves a simple arithmetic accounting of all gains and losses in each reach of the river basin being analyzed. After natural flow conditions have been reconstructed for each of the stream gage records, these natural flows are used for filling in or extending missing records at selected gages and for generating sequences of natural flows for ungaged drainage areas. This is accomplished primarily through computerized mathematical multiple-correlation and operational hydrology techniques. The result of the work at this point is a sequential set of "reconstructed" and "filled-in" natural flows for each key point throughout the entire river basin. All substantial adjustments necessary to remove from the observed records the trends introduced by the activities of man have been accomplished at this point; all streamflows at each key point are complete for the selected period; and the natural flows can be used directly for various planning studies.

The flows that can be expected to occur under various future conditions are generally necessary for project planning purposes and the development of practical, long-range, basin-wide management plans; thus, the final step is designed to adjust the historical natural flows to develop a sequence of projected unregulated streamflows. Generated, or stochastic, sets of flows and related hydrologic parameters may also be developed from the natural flows for any given set of postulated future river basin conditions.

In addition to numerous computerized analytical techniques developed to speed computational work on adjustment of specific parameters, a general streamflow accounting model which automatically adjusts all flows at each key control point for each parameter has been developed for the study. This model greatly reduces the computational effort.

The results of the Hydrologic Data Refinement Study are a consistent set of streamflow records usable for planning purposes. Any alternative set of future basin conditions can be superimposed on these streamflows to evaluate future water availability. The principal limitation to this technique is the reliability of the basic data used in natural streamflow reconstruction. Much of these data must be estimated, thus reducing the veracity of the final results. The planner must be cognizant of these shortcomings when using the refined streamflow data.

Synthetic Hydrology

The analytical models previously described in this chapter enable the planner to evaluate deterministically a large number of alternative plans and operational criteria to determine which of those best meet the goals and objectives specified at the initiation of the planning process.

These activities have had good results, are generally well accepted, and represent a major step in improving man's capability to accumulate knowledge and gain insight about the problem he is trying to solve before having to make, in many cases, irreversible decisions about the destiny of a limited water and related land resource. Terms such as minimum cost, maximum return, and maximum net benefits have emerged, and have been used extensively as the basis for quantifying optimality.

However, in the process of developing evaluative criteria for finding the optimal, planners have paid little attention to quantifying explicitly the impact that risk and uncertainty have on the decision process. For example, the hydrologic risk portion of the planning process has normally been included implicitly in specified assumptions; thus, many water supply reservoirs are designed to meet projected demands in all droughts that, on the average, occur more often than once in any 50-year period. A priori value judgments such as this, for the most part, are based upon what is expected to be conservatively adequate and not necessarily on what is expected to be economically efficient, or optimal. Thus, the impact that various drought characteristics have on economic benefits, plan performance, or user repayment capability, in many cases, is assumed away in the probability of exceedence assumption, or more basically, in an improperly stated set of objectives.

To provide more information to the planner on the effect of hydrologic variability on alternative water development plans and system operational procedures, the techniques of stochastic hydrology have been introduced into the planning-modeling process. Stochastic hydrology, or synthetic or operational hydrology as it is sometimes known, involves developing a number of hydrologic sequences for a given location (streamflow, precipitation, evaporation), each with similar statistical characteristics to the historical hydrology at the location of interest.

The primary objective of a stochastic data generation model is to produce stochastic sequences that reproduce specific characteristics of the historical data records. If the generation model is properly developed and applied, the resulting stochastic data sets contain, by definition, statistical properties similar to those data observed and used as input to the model. If this is the

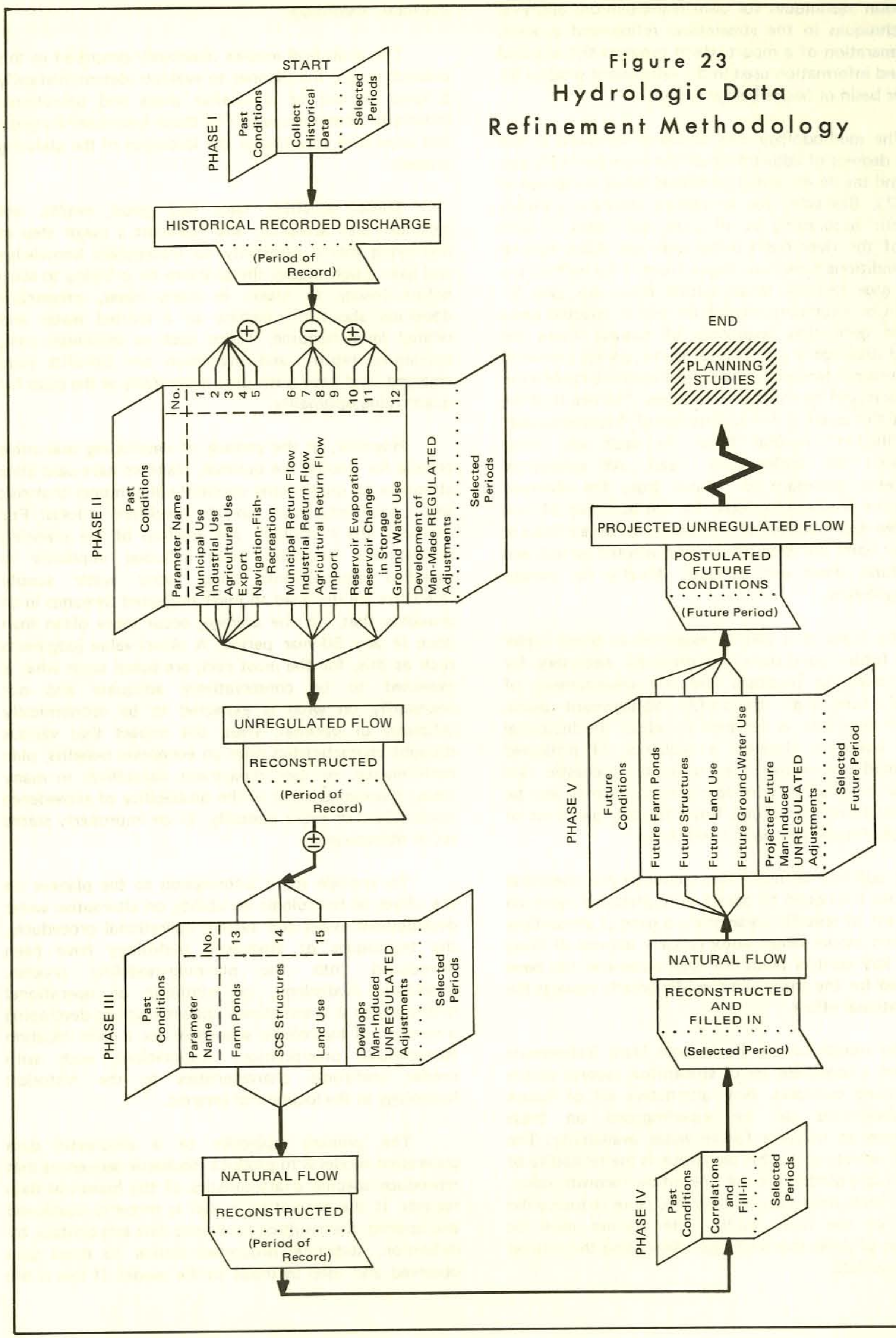


Figure 23
Hydrologic Data
Refinement Methodology

case, the stochastic sequences generated can be utilized to provide a variety of possible combinations of sequences of unique events, extremes, and certain conditions not yet documented historically but of which the historical sequence represents one possible combination. The statistically generated sequences enable the user to explore a wider spectrum of potential hydrologic events than the historical data provide, to test a design plan a facility, schedule an operational pattern, or otherwise consider the possible range of conditions at selected locations. The application of such procedures should increase the confidence of the planner that a proper decision is being made.

Typically, the data available on the stochastic nature of hydrologic system inputs consists of a limited set of observations (e.g., monthly rainfall, runoff, and evaporation data at desired locations in a river basin). Very rarely is there considered to be a sufficient period of record available (even after missing data are estimated) to span all possible ways that the phenomenon being analyzed might occur. Similarly, little attention is normally given to evaluating the relative accuracy or degree of uncertainty associated with each set of recorded observations in light of how its use may affect the solution obtained.

It is known, however, that there is a large amount of information contained in recorded data that is not effectively used when using the data only in their original order of observation. Many other possible orderings of the same data, in conjunction with other magnitudes of each data event, can be statistically inferred from information contained in the available recorded data. Therefore, it is slowly becoming accepted practice in hydrologic studies to examine the cross-correlation, auto-correlation, and other important statistical characteristics (e.g., mean, standard deviation, and skew) of the recorded data for several related data types, locations, and intermittent periods. It is also becoming common to develop, from these statistical relationships, models that fill in the missing data and then generate for further analysis any number and length of related stochastic data sequences (Beard, 1965).

Stochastic hydrology fill-in and generation techniques extract statistics from the historical records. These statistics summarize central tendency, dispersion, and persistence of the data. The statistics are used to construct a model; the coefficients of the model are estimated from the data. Stochastic data sets produced and their resultant statistics have the same properties (within sampling errors) as the historical statistics.[3] The statistics used in these models include the mean, the standard deviation, and the skewness. The mean, a measure of central tendency, is indicative of the total amount of water resource available at a site. The standard deviation is a measure of the temporal variability of the resource at the location, while the skewness is a measure of the occurrence of extreme high or low events. In addition to these statistical characteristics, which are those taken at the site of interest, there are often significant correlations between hydrologic events at adjacent sites. These spatial dependencies can be considered in the stochastic hydrology analysis by developing cross-correlations between adjacent sites. For situations where low-flow events tend to follow other low-flow events and high-flow events tend to follow other high-flow events, persistence may be a factor for consideration. Matrices of lag correlations of observations of each gage in the current time period with itself and with each of the other gages in the preceding time periods are used to describe such temporal dependencies. A so-called "Markov" assumption is imposed in such cases (Fiering, 1967).

In most areas of the country continuous historical hydrologic records, and in particular steamflow records, are of insufficient number and length to adequately describe a water supply system's hydrologic characteristics. In order to enhance the utility of the hydrologic data base, correlation techniques are used to estimate missing data in noncontinuous records. The stochastic hydrology methods discussed above are ideal for filling in discontinuous historical records of hydrology. Since the methods, by design, preserve the important statistical characteristics of historical hydrologic records at a site, they are obviously well suited to filling gaps in historical records.

Many researchers have discussed stochastic flow simulation (Beard, 1965; Chow, 1964; Fiering, 1967). Two procedures are known to be currently operational for filling data and generating stochastic sequences. Procedure A was obtained from the Corps of Engineers Hydrologic Engineering Center and performs both fill-in and hydrologic sequence generation in an integrated computational operation (Hydrologic Engineering Center, 1967; Texas Water Development Board, 1974). Procedure B derives from two coupled computations; fill-in is performed by a computation technique developed by Water Resources Engineers, Inc. (Texas Water Development Board, 1971b), and hydrologic sequence generation is performed by a method developed by the Federal Water Quality Administration (Young and Pisano, 1968). More detailed discussion of the procedures are presented in the literature citations.

Each procedure mentioned above involves a transformation of historical hydrologic data at each site to an approximately Gaussian normal distribution; estimation of the first three moments of the distribution; development of intrasite cross and serial correlations; use of these correlations for filling gaps in historical records or for generating stochastic sequences; and reversing the initial transformation to obtain the filled or generated hydrologic records.

---

[3] "Statistical properties" as used here implies that statistical tests of significance of differences applied to the two sets, historical and stochastic, would not be expected to reject the null hypothesis that the differences between the two sets equal zero.

Two attitudes prevail concerning the generation of the required number of stochastic sequences for the analysis of a particular planning problem. They are as follows:

- Generate more sequences than could possibly be required, striving to insure that the population of possible future occurrences is spanned, and then draw a sample of sequences from this large representative population. This is an attractive procedure if the generation cost is low in comparison to the sequence analysis cost; generally this is the case in hydrologic systems.
- Generate a few sequences (five or six) and compare the system's performance with each sequence. Then, compute the expected performance, the standard error of the performance, and the total number of sequences required to reduce the standard error of the expected performance to an acceptable level. If the distributions are normally distributed, the standard error should decrease in proportion to the square root of the total number of years in the sequences. This procedure is attractive if the generation cost is relatively high with respect to analysis costs; this may be the case in complex hydraulic systems.

Typical examples of filled and generated stochastic streamflow records are shown in Figure 24. In both cases it can be readily shown that the appropriate statistical characteristics of the historical streamflow have been preserved.

The use of data generation and fill-in techniques requires care in application. Four data attributes are identified which may cause the techniques to fail completely or partly in their objectives; the four attributes violate the assumptions which underlie the procedures. The four items of concern are:

- The numerical truncation which is required to constrain values to be greater than zero. This truncation has the effect of shifting the mean of the generated data to values higher than the historical data. Data having coefficients of variation greater than 0.5 cause truncation problems.
- The form of the transformed probability distributions at each site. If the marginal distribution is not Gaussian (or cannot be transformed to approximate a Gaussian distribution), problems in preserving moments can be expected. A practical guide is to check all marginal distributions prior to the implementation of generation techniques.
- The degree of cross-correlation between sites. Should there be too strong a relationship (correlations approaching unity), the resultant collinearity causes numerical problems; the determinate of the correlation matrix approaches zero which makes matrix inversion subject to numerical error. In such cases, sites of lesser importance or sites which can be estimated from other nearby sites in the set should be removed to reduce collinearity.

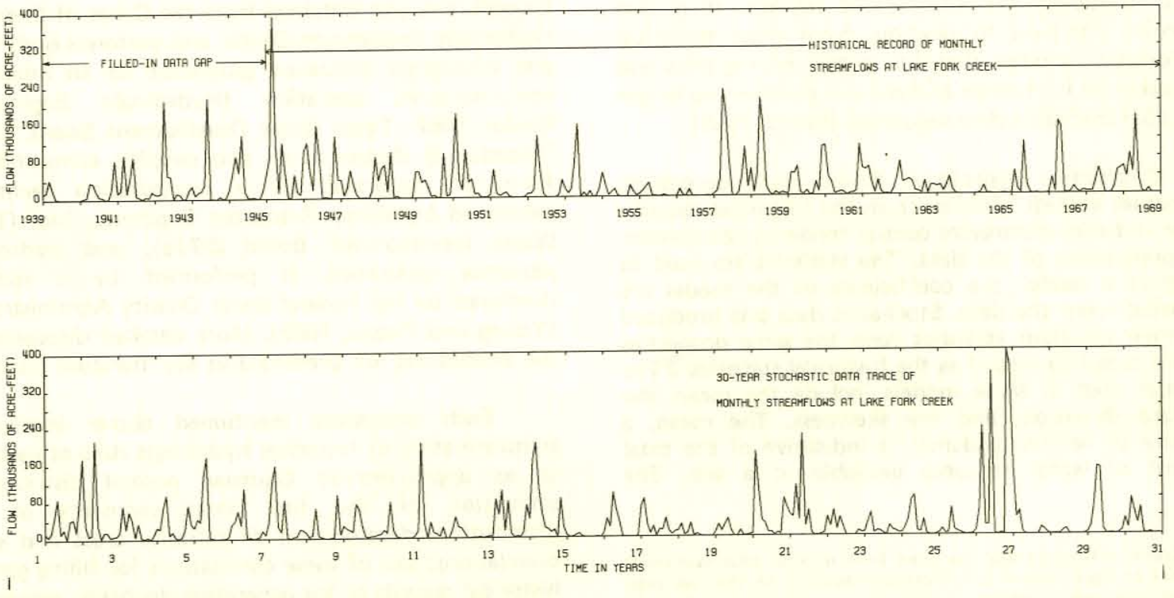


Figure 24.—Filled-In Historical and Generated Streamflows Using MOSS-III

- The effect of trends. Quite often man's land-use activities over time have produced changes in runoff. For example, the amount of imprevious surface in a catchment area may increase through time and thereby cause the average runoff to increase as a function of time. Historical data for use in planning should be checked for trends and any trends removed to provide statistically stationary data for data generation purposes. The Hydrologic Data Refinement Study, previously described, is designed to remove trends prior to data fill-in and hydrologic sequence generation. Projected trends in water use, land use, etc. can then be introduced into the filled and generated sequences in order to evaluate man's effect on water availability.

An example of a troublesome data record is that from the stream gage Sulphur River near Darden. The stream essentially goes dry (probability of runoff being less than 10 cubic feet per second in October is estimated to be 41 percent) during certain months. This finding evolved after problems in stochastic generation for this gage were noted. Analysis of the observed data revealed a bimodal log transform distribution for the gage for the month of October as shown in Figure 25. The October distribution is based on 27 observed flows. Neither Procedure A nor Procedure B can cope with bimodal distributions. Other gages analyzed did not show bimodal distributions. The lesson, however, is clear: check the distributions and relate these to the assumptions of the generation techniques.

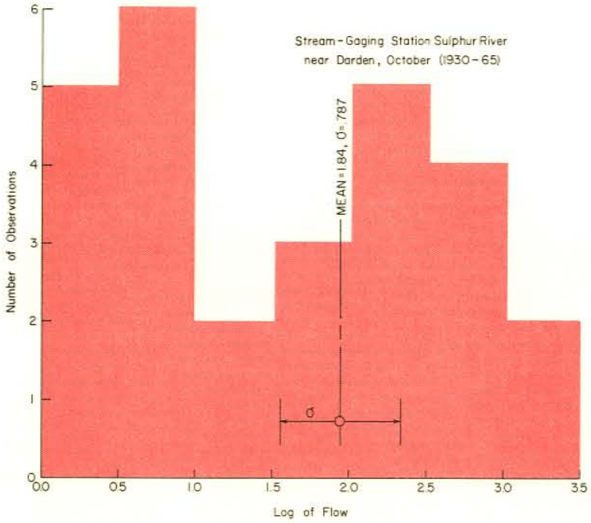


Figure 25.—Bimodal Distribution of Monthly Streamflows

Sensitivity Analyses

One of the foremost advantages of the systems of simulation approach performed on high speed computers is the ability to analyze, rapidly and exhaustively, the sensitivity of a particular plan and its alternatives to variations in some of the factors which effect the decision process the most (e.g., capital costs, power costs, interest rates, etc.). Sensitivity analyses are applicable to many of the different simulation techniques described herein. Typical variables that might be analyzed in planning a water supply system include:

- specified water requirements to be supplied,
- monthly distribution of the water requirements,
- gross evaporation rates in both the demand and supply areas (if different),
- quantity of import water available,
- reservoir inflow and storage capacities,
- precipitation variability as it effects the water demands and available supplies (e.g., runoff, ground-water recharge, etc.), and
- different methods of discounting the cost of implementation plans.

In some of the environmental simulation methods, the sensitivity of dissolved oxygen concentration to stream temperature, the sensitivity of lake ecosystems to selective withdrawal, and the sensitivity of estuarine hydrodynamics to changes in bathymetry can be evaluated in a similar manner. The list of analyses is unending and can provide the planner with a great deal of information on the capability of a planned system to meet its objectives or the sensitivity of some physical phenomenon to man-made changes. The methods of sensitivity analysis, using environmental simulation models, are ideal for analyzing the impacts of man's activities on the environment. Simulation models are one of the few techniques available which actually show the cause-effect relationships between the biological and physical environments.

Typical examples of sensitivity analyses are given in the next chapter in the context of solution of an example problem using simulation techniques. These examples will illustrate to the reader some of the potential of the use of sensitivity analyses to expand his information for better planning and goal satisfaction.

VI. AN EXAMPLE PROBLEM—THE TEXAS WATER SYSTEM

As an illustration of the application of the models and simulation techniques developed by the Board in its planning research, an example problem showing the use of several of the programs described herein has been summarized from Texas Water Development Board Report 131. The example problem is not intended to show the "best" or only way of using these models, but rather is intended to show a typical analysis for which the models are well suited. Report 131 includes complete detail on the model application to the example problem.

The portion of the Trans-Texas Division from the Texas Water System that is used in the example is comprised, as illustrated schematically in Figure 12, of three major components: a major demand area lying primarily in the High Plains of West Texas, an in-state supply area comprised of two river basins in East Texas, and an out-of-state source of water which may be drawn upon to meet required demands in excess of in-state supplies. A distinguishing feature of this system is its overall size; more than 700 miles separate the major demand centers from the sources of imported water. In addition to the hundreds of miles of interconnected canals and natural waterways, there are numerous reservoirs in the system. Pumping facilities will be required to lift flows through about 3,200 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 limited,
- the only sources of water supply in the major demand area (West Texas) are ground waters and these are being rapidly depleted,
- the potentially developable reservoir sites in the in-state supply basins have a cumulative capacity to supply the maximum system demand for only a single year of operation,
- the surface water supplies of in-state basins and the demands for water are highly variable, both seasonally and annually,
- the proposed sources of imported water can be drawn upon for only a portion of the year, and
- the maximum demands on the system may be expected to occur during the months when import water will not be available and runoff is low, hence peak demands must be met primarily from stored supplies.

For the example problem, an over-specified[4] set of 12 reservoirs, 26 pump-canals, and 8 river reaches has been identified that might be necessary to accomplish the desired water transfers. The objective was to find which combination of these reservoirs and canals will satisfy a set of specified demands for water at minimum total expected cost, where both the demands for water and the surface water inflows to reservoirs (supply) have stochastic components.

Of the 12 reservoirs considered, 3 are existing, 1 is in an early phase of construction as of January 1974, and 8 (including one enlargement of an existing reservoir) are proposed to be constructed during the period of demand buildup. The eastern part of the network encompasses the Sulphur River and Cypress Creek basins. The eastern portion extends a distance of nearly 200 miles between reservoir 12 (on the eastern boundary of Texas - see Figure 12) and junction 14 (just north of the Dallas-Fort Worth area). Westward of junction 14, a large proposed pump-canal carries water over a distance of nearly 400 miles to two large terminal reservoirs, Caprock and Bull Lake (reservoirs 2 and 1) in the High Plains area of West Texas.

Because of the dominance of irrigation demands in the system, almost 90 percent of the total demand occurs at junction 17 between Caprock and Bull Lake Reservoirs. Smaller demands for local municipal, industrial, and agricultural use are imposed at other reservoirs and junction points. The average pumping lift across the eastern portion of the system (reservoir 12 to junction 14) is about 350 feet, while the lift westward to the High Plains is roughly 2,800 feet. Over the entire system the average lift is roughly 5 feet per mile.

The volume and cost characteristics of the 12 reservoirs in the example problem are presented in Table 2. Most of the reservoirs have been sized as shown in the Texas Water Plan to provide a maximum volume consonant with topography and geology of the site and which is sufficient to maintain a firm yield of the tributary inflow over the historical period (1941-1957). This was done to reduce the amount of computation time required to demonstrate the solution methodology described herein. A total capacity of 11.32 million acre-feet is provided, slightly more than the average annual local runoff.

Figure 12 shows the regional location of the water-supply reservoirs. In contrast to the 40 to 50 inches of average annual precipitation in the Sulphur River and Cypress Creek basins (Figure 3), the demand area has an average annual precipitation of approximately 18 inches.

---

[4] Over-specified refers to the fact that more reservoirs and canals were included in the analysis than were known to be necessary.

Table 2.—Reservoir Characteristics and Costs

NUMBER	NAME	STATUS	AVERAGE ANNUAL INFLOW (THOUSANDS OF ACRE-FEET)	VOLUME* (THOUSANDS OF ACRE-FEET)	UNIT COST (DOLLARS PER ACRE-FOOT)	TOTAL COST (MILLIONS OF DOLLARS)
1	Bull Lake Reservoir	Proposed	—	3,000	25.0	75
2	Caprock Reservoir	Proposed	—	1,500	37.3	56
3	George Parkhouse I Reservoir	Proposed	106.9	635	42.5	27
4	Marvin C. Nichols Reservoir	Proposed	1,600.2	2,457	42.3	104
5	Black Cypress Reservoir	Proposed	213.1	824	41.3	34
6	Lake Cypress Springs†	Existing	42.9	73	—	—
7	Cherokee Trail Lake‡	Proposed	113.2	314	38.2	12
8	Marshall Reservoir	Proposed	399.4	782	35.8	28
9	Cooper Lake	Under Construction	231.4	311	93.2	29
10	Lake Texarkana	Existing (Proposed Enlargement)	193.1	929	21.5	20
11	Lake O' the Pines	Existing	327.5	255	—	—
12	Caddo Lake	Existing	233.9	252	—	—
	TOTAL		3,461.6	11,320	34.0	385

---

* The reservoir volume at the top of the conservation pool.

† Formerly known as Lake Franklin County; name changed by owner April 2, 1971.

‡ Formerly known as Titus County Reservoir; name changed by owner March 5, 1973.

Canals in the system shown in Figure 12 were sized in stages to allow for capacity expansion as demand builds up over the planning horizon. Cost variations with canal size were described by second-order polynominals - one for each canal.

The methodology used for solving the example problem using the simulation models was comprised of six major steps, none of which is different from current water resource planning analyses, but which collectively represent a more systemized and thorough analytic treatment of the risk and uncertainty associated with the problem and the decision process than was previously available. These six steps essentially provide the framework of this example analysis and are designed to answer the following four questions:

- Which of an over-specified set of reservoirs and canals should be constructed?
- When should each of the reservoirs and canals be constructed?
- How large should each of the reservoirs and canals be at various points on the demand-buildup curve?
- How should the resulting optimized system of canals and reservoirs be operated, both during and after the period in which facilities are being added or increased in size?

Step One - Identification of Objectives and Goals

Step One consisted 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 a solution can become obvious or an optimal implementation plan can be found. Meeting demands at minimum expected cost, with tolerable shortages, is only one of the possible objectives that normally could be specified; however, for the purposes of this example and the modeling capability, it is satisfactory for demonstrating the worth of explicitly evaluating risk and uncertainty in the planning process.

Step Two - Analysis and Development of Data Base

Step Two consisted of developing a comprehensive data base for use in Steps Three through Six. This step was comprised of two major types of data preparation activities. The first activity was that of developing, for use by the simulation and optimization models, a sound historical and 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 was comprised of developing parameters which describe the system and the problem being studied, such as

- cost-capacity-elevation-area relationships for all of the reservoirs and canals being considered in the analysis,
- the interest 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.

From the hydrologic viewpoint, this step, if done correctly, involves considerable effort in the detailed refinement of basic surface and ground water data at various projected levels of basin development (e.g., 1980 conditions, 2000 conditions, etc.).

To enhance the results of this step, trend analysis programs, fill-in programs, stochastic data generation programs, and flow refinement and projection programs are used to help preserve the appropriate cross and serial correlations within all 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. The programs used in this step were FILLIN-I, MOSS-III, and DEMAND-II.

One of the unique characteristics of this methodology is the treatment of the element of risk (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 (e.g., 98) of rainfall, runoff, evaporation, and unit demands for water, are required. For the example problem, 36-year historical and stochastic data sets were used. The 36-year period corresponds to the demand-buildup period (1985-2020) as shown in Figure 12.

The need for treating risk and uncertainty in this manner arises from the recognition that in many irrigation service areas significant useful amounts of rainfall occur during many years. That rainfall reduces the amount of irrigation water needed to serve a given irrigated acreage, and thus, has an impact on the efficient design and operation of the required storage and transfer facilities. Since rainfall contains a stochastic component and there exists a definite deterministic relationship between rainfall and the need for supplemental irrigation water, a straightforward method to transpose the stochastic characteristic of the rainfall data to the demands for water is to use a soil moisture and consumptive use model, along with rainfall data, gross pan evaporation data, and other soil and cropping data and irrigation efficiency to generate monthly unit-acre irrigation demands.

Because the procedure is structured on a typical cropping pattern and a unit-acre basis, the results must be multiplied by the number of acres within each irrigation subdistrict. The total demands for each subdistrict (plus losses) must then be summed to get the actual total monthly demand for irrigation water at each demand point within the network structure of reservoirs and canals.

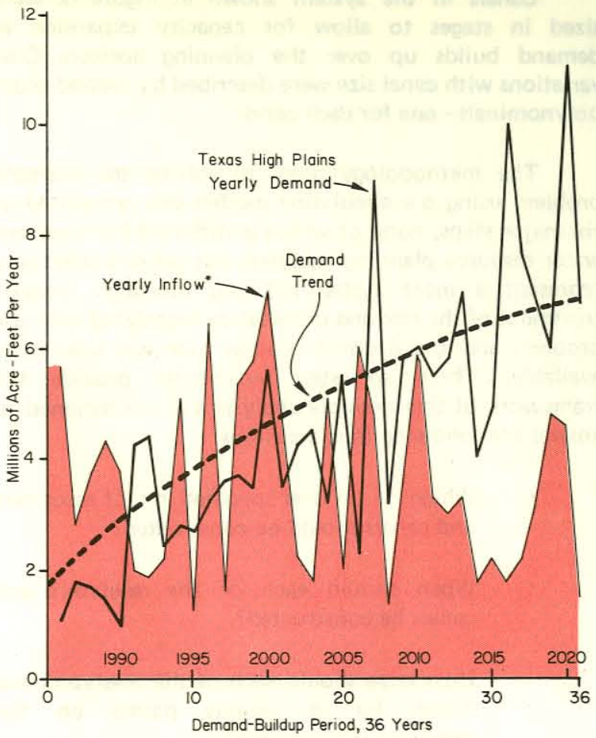
For the demand points within the Texas High Plains this procedure results in a demand sequence that varies about a trend line as shown in Figure 26. The trend line is a direct function of both the number of acres that are irrigated with surface water and the average annual rainfall contributions, whereas the jagged line represents the actual water usage based upon rainfall and evapotranspiration stochastic variability. The trend line shown in Figure 26 is comprised of the average stochastic irrigation demand plus a non-stochastic municipal and industrial demand quantity.

The 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 26 for the 36-year demand-buildup period. Close inspection of the data supporting Figure 26 will reveal that after about year ten, the average supply is insufficient to meet the average demand. Therefore, for most of the time during the demand-buildup period, import water is required to meet, on the average, demands for water imposed by a specified irrigated acreage.

Net lake surface evaporation data are also computed. This is done using the rainfall and gross pan evaporation data for both the supply and terminal storage reservoirs.

Step Three - Plan Development Based on Historical Data

Step Three consisted of a "first-pass" analysis of the river basins and portions of river basins comprising the multibasin planning problem. The purposes of this analysis were to



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

Figure 26.—Stochastic Variability of Inflow and Demand

- 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 and flood control viewpoint, various locations and sizes of possible reservoirs were investigated in an attempt to find the storage arrangement that controlled the runoff in each watershed at minimum unit storage cost (dollars per acre-foot of storage), yet assured that the major storage reservoirs, if possible, were near the major in-basin demand points.

At first, import water was considered to be unavailable. However, later in this step, any available import water was included in the analysis and used to increase the demand level imposed upon the system. Oversizing the demands during planning studies will insure that expressions or simulations of shortages will occur, and that the penalty costs for incurring shortages will help determine the optimum implementation plan in a manner described in Steps Four and Five.

To aid in this process SIMYLD-I, an early version of SIMYLD-II, was developed. It 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 were 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. Also, 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 (Figure 26).

A set of reservoirs in the supply basins, having specific locations and sizes such as those shown in Figure 12, is a partial result of this step.

The more closely the user is able to estimate the level of both the firm yield (the condition of no shortage) and the actual yield (the condition of optimal shortage) of a multibasin system, the less analysis and fewer simulation iterations are required to find the level of demands that can be optimally met. However, to be able to closely estimate the optimal based upon firm-yield information, considerable experience is required in applying the models to various types of problems. In the example problem presented herein, Figure 27 indicates that systemized operation causes about a 15 percent increase in the firm yield of the individual reservoirs when both the Cypress Creek and Sulphur River basins are operated as a composite system. Each basin operating by itself in a systemized manner resulted in a total increase of about 13 percent. The sum of the firm yields of the reservoirs in each basin, acting independently without the pump-back facilities, was approximately 2.2 million acre-feet per year (63 percent of the average annual runoff); whereas, using the results of Steps Four and Five which "optimize" the size and operation of each of the required canals, river reaches, and reservoirs, the actual yield (not firm yield) was increased to approximately 3.1 million acre-feet per year or 89 percent of the average annual runoff of 3.5 million acre-feet.

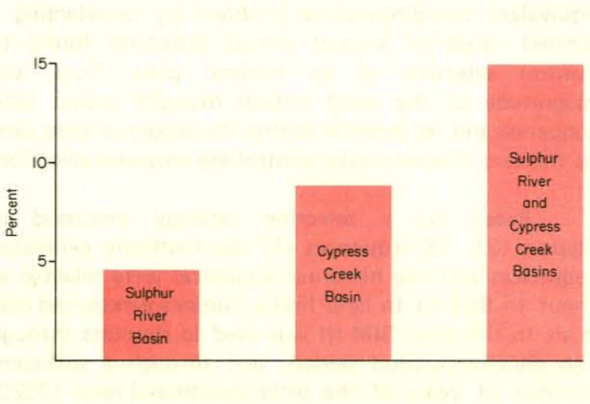


Figure 27.—Increase in Basin Yield Resulting From Systems Operation of All Reservoirs

Step Four - Plan Improvement Based on Historical Data

Step Four used SIM-III and AL-II[5]/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 as 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. SIM-III and an analysis period (e.g., 36 years) equal to the time period over which demands are increasing was used; however, the procedure is independent of the length of simulation period used as long as it is of sufficient duration to generate a realistic total-cost response of the system being simulated.

For the example problem, finding the optimal development plan began with analyzing the full-development condition (e.g., the 2020 condition). This was done to obtain an approximate size and shape of the ultimate system configuration, especially the size of that portion of the canal facility (the ditch portion) that cannot be increased in size (staged) over the demand-buildup period shown in Figure 26, but must be built initially at 2020 level size. In the example problem, it was assumed that the ditch portion of the canal included right-of-way costs, relocation costs, bridge costs, pump-station foundation costs, ditch excavation and living costs, and associated items; the pump, motor, power, and their housing components are the portions of the canal facility that can be staged. The 36-year historical hydrologic sequence projected to 2020 conditions (Figure 26) and the 2020 level demand data, developed in Step Two, were used as input to SIM-III along with a whole array of physical costs and control parameter data. The over-specified network of potentially attractive canals and river reaches shown in Figure 12 was also used.

Based upon a series of "first-try" 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

---

[5] The SIM-III and AL-II models were predecessory of the SIM-IV and AL-III models, respectively, which were discussed earlier in this report. The newer versions have enhancements to increase the utility of the models, but the basic models and their results are the same as their predecessor versions.

- 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 constraint of each of the canals left in the network was 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 value factor equal to unity, and (2) the average annual operation costs multiplied by the total area under the 100-year present value curve.

Upon preliminarily sizing 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. At each of the demand points, SIM-III was used in an iterative manner based upon a steepest-gradient search philosophy discussed in detail in Report 131. The point of observation for measuring the economic response of the system at each of the demand points (e.g., 1990, 2000, 2010, and 2020) was the beginning of the planning or construction period (e.g., 1985). Again, a 100-year economic life, a 4 percent discount rate, and a 36-year simulation period were used in the demonstration problem.

The need to specify staging time increments was basic to the analysis procedure. The time increments need not be equal. In fact, their lengths should be based upon an analysis of the shape of the demand-buildup curve, the shape of the present value curve, shortage-penalty costs, excess-capacity costs, and the greater cost of constructing facilities in stages instead of constructing them to their ultimate size initially.

Step Five - Plan Optimization Based on Historical and Stochastic Data

Step Five was 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. 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 what changes in the "good" plans derived in Step Four are required to cause more cost-effective performance, and
- find the single implementation plan (the minimum-cost plan) which performs better against the historical and synthetic buildup in demand and projected supply sequences than any other plan.

The first portion of this step was comprised of selecting a respresentative few of the 90 or more synthetic supply and demand sequences generated in Step Two for use with the simulation and optimization models. This was done using a procedure that

- analyzes the specific drought characteristics of the historical sequences plus each synthetic sequence,
- categorizes the set of 99 or more sequences into selected subsets according to their drought characteristics, and
- selects, in a manner to reduce small-sample bias, a representative few of these sequences that closely approximate the variability contained in the 99 sequences.

In order to select a small representative number of sequences from a large number, it is desirable to determine a single characteristic of the sequences that substantially influences the performance of the system. If there is more than one important independent characteristic, it is necessary to classify sequences on the basis of each characteristic. For example, for hydrologic systems there exists the strong conviction among many planners that the magnitude of the most critical drought within a sequence is an especially important characteristic. Another important characteristic is the location of the drought within the sequence, if, over time, the staging of facilities to meet an increasing demand for water is to be analyzed. The duration of the drought is also important in influencing the impact of the drought on system performance.

Although three important drought characteristics (magnitude, location, and duration) were identified for the example hydrologic system, it was found that the three-dimensional problem could be reduced to an equivalent two-dimensional problem by preselecting a limited range of critical period durations found to control selection of an optimal plan. Thus, the magnitude of the most critical drought within each sequence and its location within the sequence were used as the two characteristics controlling sequence selection.

Based on a selection strategy discussed in Report 131, 18 sequences (17 stochastically generated sequences and one historical sequence) were selected as input to SIM-III to help find a minimum-expected-cost plan. In this step, SIM-III was used to simulate through the demand-buildup period, and through a sufficient number of years of the ultimate-demand-level (2020) plan, to generate a present value cost of system performance both during (1985-2020) and after

(2021-2084) the demand-buildup period. As in Step Four, a 100-year economic life and a 36-year simulation period were used.

In this analysis location of drought during the demand-buildup period was important to the success and meaningfulness of the solution; therefore, multiplication of each year's simulated annual costs by corresponding present value factors was used to compute the total present value of annual costs. The capital expansion costs incurred at the various staging points are, of course, also multiplied by the appropriate present value cost component. For the years after the demand-buildup period (2021-2084), the simulated average annual cost component was multiplied by the area under the last 64 years of the present value curve. The three present value cost components for all 18 sequences are added together and divided by 18 to compute the average total present value cost. This total cost was then used as the single measure of cost response for finding the minimum-expected-cost implementation plan.

The type of information provided the planner from the preceding analysis is as shown in Figure 28. This figure shows the results of a number of analyses of the system cost response as the staging time and size of the major canals in the example system were varied. The shape of the cost response surface is illustrative in regard to the sensitivity of the total system cost to the particular canals being analyzed and shows the wide range of alternatives evaluated.

Step Six - Variability and Sensitivity Analysis

Step Six was the last major step in the multibasin planning example, and consisted of an extensive variability and sensitivity analysis. The purpose of this analysis was to subject the minimum-expected-cost plan in Step Five to conditions other than the specified "best estimate" conditions assigned to many of the independent variables at the beginning of the analysis. In essence, this step involved evaluating the economic and physical performance of the minimum-expected-cost plan by taking a single-variate cross-section on every variable supplied as input to the SIM-III program. Similarly, multivariable cross-sections were also taken where the results could be meaningfully interpreted. Typical data varied include the canal cost data, the reservoir cost data, the initial storage conditions, the buildup rate in the number of acres to be irrigated, the cropping pattern data, 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 data, and the unit power cost data.

It is particularly informative to show the results of these sensitivity analyses since this type of information is rarely available to the planners from conventional planning techniques and is one of the most powerful analytic tools made available to the planner through the use of these methods.

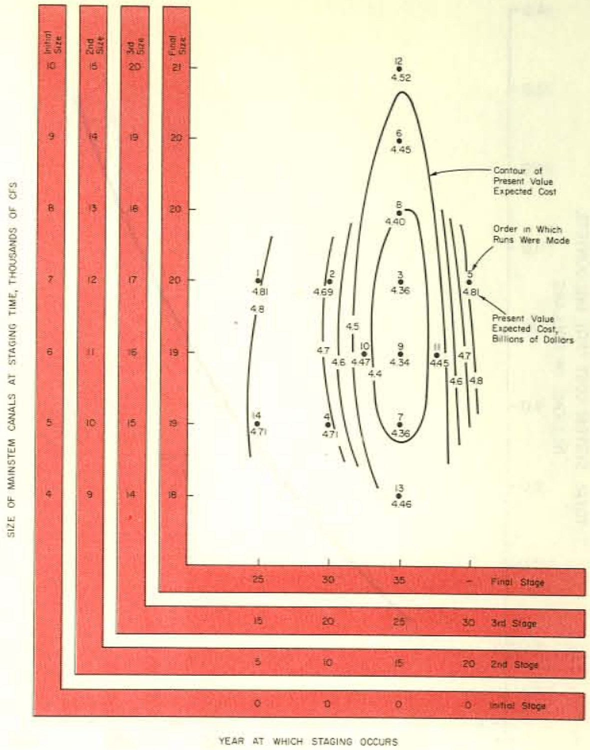


Figure 28.—Present Value Cost Response Surface Showing Canal Sizes

Response to Changes in Requirements for Water

The projected requirements for water constitute some of the most important data in water planning studies because they furnish the driving force creating the need for water development. Water requirements to be supplied by proposed projects are developed based on expected increases in population or industrial and agricultural activities. As in all projections, inherent uncertainties are associated with the magnitude of these requirements. If water demands develop at a greater or lesser rate than that projected as a basis for planning, the operational requirements for the system will change.

Consider the information shown in Figure 29. The change in total system cost (capital plus operation and maintenance cost) is depicted for water requirements varying above and below those projected. The projected water requirement corresponds to the central plot of the curve (corresponding to a cost of $9.18 billion). Note that the rate of change of total system cost increases at a greater rate as demands rise. Water requirements shown are cumulative values for the 36-year planning period at the 2020 level of demand.

Irrigation-Demand Sensitivities

Unit-acre demands for irrigation water were computed by the DEMAND-II computer program. The

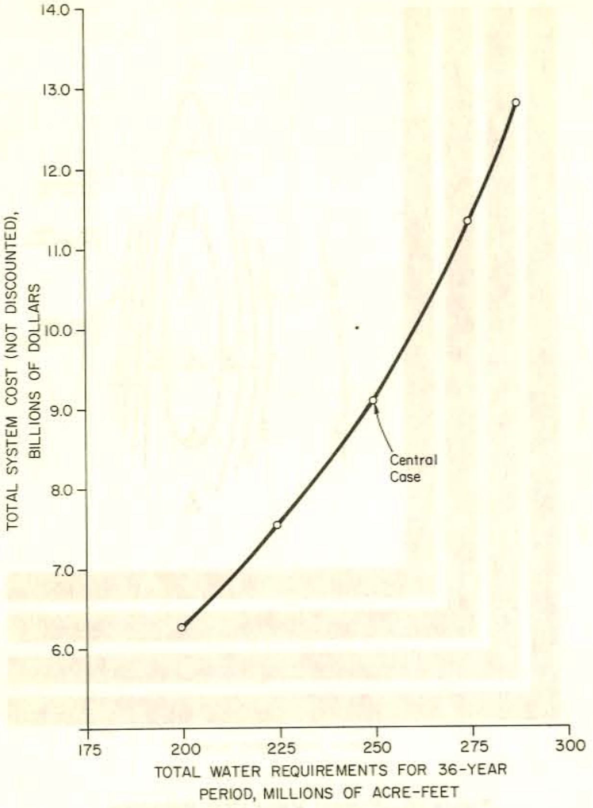


Figure 29.—Sensitivity Analysis—Total Water Requirements

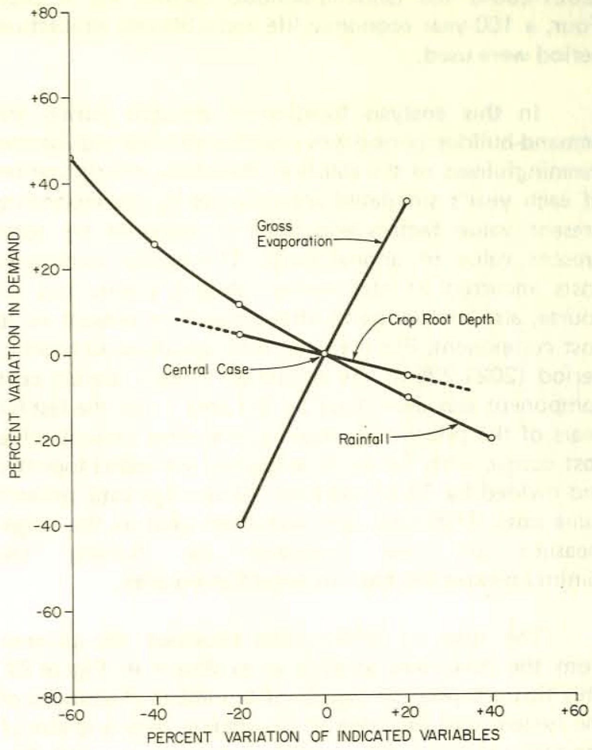


Figure 30.—Sensitivity Analysis—Irrigation Demand Variables

product of this computational procedure is a sequence (or sequences) of monthly irrigation demands reflecting the stochastic properties of the quantities upon which the water balance is based, e.g., rainfall and evaporation.

The sensitivity of this model is illustrated in part by Figure 30. In this figure percent variation for the total cumulative demand over the 36-year planning horizon, 1985-2020, is contrasted to percent variation for the total cumulative precipitation and evaporation in the demand area. The dominant influence of evaporation is well illustrated. A change in evaporation of 20 percent is identified with a change in demand of about 40 percent, while a comparable change in precipitation induces a change in demand of roughly 11 percent.

The effect of the assumed depth of root penetration is also illustrated in Figure 30. The relative insensitivity of model response to this variable is suggested by the fact that for these conditions a 20 percent variation in root depth caused only about a 5 percent change in estimated demand.

Firm-Yield Sensitivities

Firm-yield analysis plays an important role in an optimal water resource development plan. During that portion of the analysis, most of the reservoirs were sized and reservoir operation criteria were preliminarily specified. Therefore, it should be of interest to know how accurate the yields being computed are, and to what degree the variables such as runoff, reservoir size, reservoir surface area, and evaporation rates affect the accuracy of the firm yield. To help determine this, a set of SIMYLD-I runs were made, varying the independent variables mentioned above by up to plus and minus 20 percent. The results of that process are shown in Figure 31. The figure shows that as either storage or runoff are increased by 20 percent, a corresponding 10 to 11 percent increase in firm yield occurs. Conversely, as these variables are decreased by 20 percent the yield decreases by about 11 to 12 percent. The relationship is apparently not quite linear. Figure 30 also shows that as evaporation rates are increased by 20 percent, the firm yield decreases by about 14 percent; whereas a 20 percent decrease in evaporation rates produces only a 7.5 percent increase in firm yield. In addition, for a 20 percent increase in reservoir surface area, only a 4.0 percent decrease in firm yield occurs. This relationship is apparently fairly linear because a corresponding decrease in surface area by 20 percent causes a 4 percent increase in the computed firm yield.

Response to Changes in Economic Information

As a part of the sensitivity studies, quantitative results were obtained concerning changes in economic information such as power cost for pumping and methods of cost discounting.

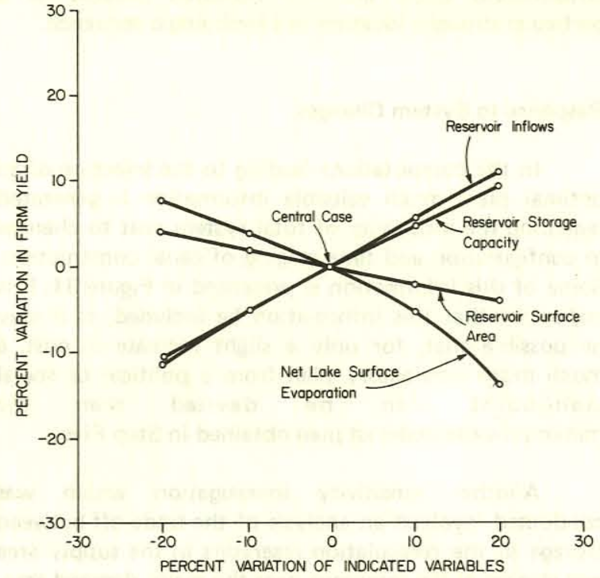


Figure 31.—Sensitivity Analysis—Firm Yield

Figure 32 illustrates the effect of variation of the cost of power on the total system cost. Power cost was varied from 3 to 5 mils per killowatthour and the total system cost resulting from a 36-year simulation was determined. As should be expected, the power cost has a direct effect on the total system cost. The magnitude of the change is important in assessing the potential effect of changes in the cost of power.

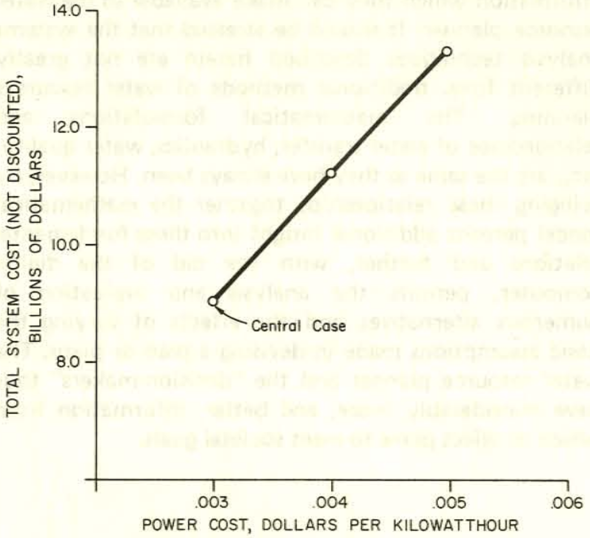


Figure 32.—Sensitivity Analysis—Power Cost

Comparative analysis of the data contained in Figure 32 and the data presented in previous figures can provide information similar to that given in Figure 33.

This figure indicates the percentage change in selected variables required to produce a 10 percent change in total system cost. This type of information can be useful in allocating effort aimed at selectively improving the planning information base. It should be emphasized that Figure 33 indicates only the relative importance of various planning variables as measured by the system cost response. The length of the bar in the figure is inversely proportional to its importance to system cost response. The percentage deviations are all measured relative to the selected "best plan" developed in Step Five. Implicit assumptions used in modeling, such as $100 per acre-foot shortage cost and system operation rules, will have a pronounced effect on the results presented.

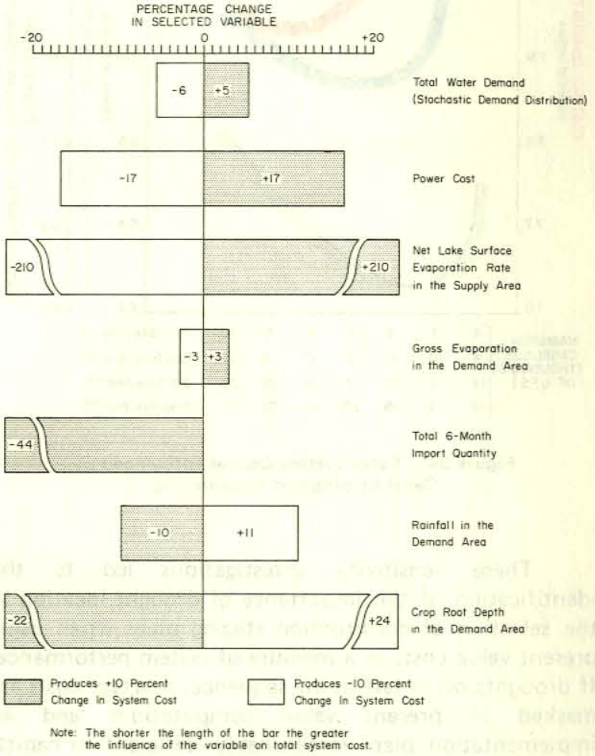


Figure 33.—Percentage Changes in Selected Variables Which Produce a 10 Percent Change in Total System Cost

Figure 34 indicates the influence of present value computations in the selection of a minimum-cost plan. The abscissa in Figure 34 represents alternative plans for sequentially staging the capacity expansion of the canal system. Four capacity expansion steps are considered, at the beginning of the project (year 0), the 15th year, the 25th year, and the 35th year. The alternate capacities for mainstem canals (canals 19, 14, 10, 9, 25, 28, 29, and 30) are given for each of the capacity expansion steps. The ordinates in the figure show the undiscounted and present value costs for the given capacity expansion plans. For each interest rate used in present value computations, a curve similar to one of the lower curves in Figure 34 is found. The curves presented in Figure 34 were developed with an interest rate of 4 percent. The apparent least-costly plan changes with both the interest rate and the number of years considered in present value computations. The importance of the economic life of the project in present value computations is illustrated.

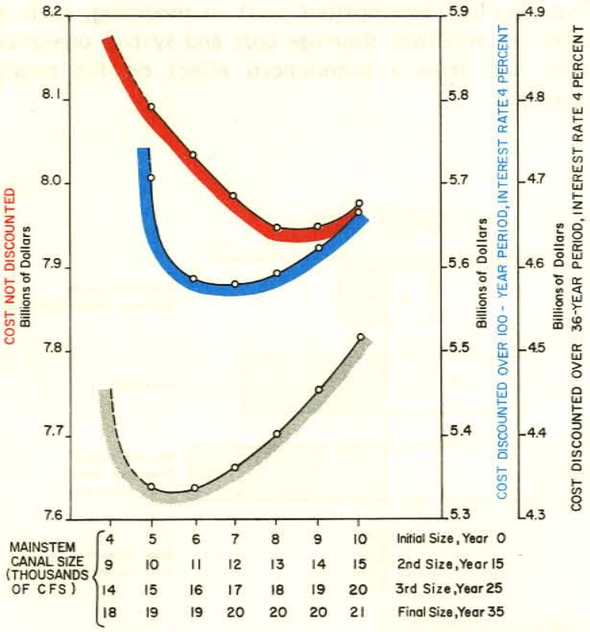


Figure 34.—Total System Cost as Influenced by Canal Staging and Discounting

These sensitivity investigations led to the identification of the importance of drought location in the selection of construction staging plans when using present value costs as a measure of system performance. If droughts occur late in the sequence, shortage costs are masked in present value computations and an implementation plan unreasonably deficient in capital facilities is indicated. For droughts occurring early in the sequence, unreasonably high levels of capital expenditures are indicated by present value computations. Because critical droughts can occur early or late in a particular sequence with equal probability, this analysis led to the development of a procedure which involves computing average annual system costs before applying present value computations so that unwarranted plans are not indicated because of a particular drought location in a hydrologic sequence.

Response to System Changes

In the computations leading to the selection of an optimal plan, much valuable information is generated regarding the sensitivity of total system cost to changes in configuration and time staging of canal construction. Some of this information is presented in Figure 34. It is important that this information be included, as it may be possible that, for only a slight increase in cost, a much more satisfactory plan from a political or social standpoint can be devised than the minimum-expected-cost plan obtained in Step Five.

Another sensitivity investigation which was conducted involved an analysis of the trade-off between storage in the reregulation reservoirs in the supply area and storage in the reservoirs near the major demand area. It was found that, even though evaporation losses are significantly higher in the demand area, it is less costly to store more water there than it is to increase reregulation storage and pumping capacity in the other parts of the system.

Summary

The preceding discussion has shown an example application of certain of the simulation techniques which have been developed by or for the Texas Water Development Board. The purpose of the example was to show how these analyses are conducted and the type of information which they can make available to the water resource planner. It should be stressed that the systems analysis techniques described herein are not greatly different from traditional methods of water resources planning. The mathematical formulations and relationships of water transfer, hydraulics, water quality, etc., are the same as they have always been. However, by bringing these relationships together the mathematical model permits additional insight into these fundamental relations and further, with the aid of the digital computer, permits the analysis and evaluation of numerous alternatives and the effects of varying the basic assumptions made in devising a plan or plans. The water resource planner and the "decision-makers" thus have considerably more, and better, information from which to select plans to meet societal goals.

REFERENCES

Beard, L. R., 1965, Use of interrelated records to simulate streamflow: Am. Soc. Civil Engineers, Water Resources Eng. Conf., Mobile, Ala., Reprint 64.

Chow, V. T., ed., 1964, Statistical and probability analysis in hydrologic data, part IV *of* Sequential generation of hydrologic information, *in* Handbook of applied hydrology: McGraw-Hill Co.

Durbin, E. P., et. al., 1967, The out-of-kilter algorithm, a primer: The Rand Corp., Santa Monica, Calif.

Fiering, M. B., 1967, Streamflow synthesis: Harvard Univ. Press.

Hydrologic Engineering Center, 1967, Monthly streamflow synthesis: U.S. Army Corps of Engineers.

Pinder, G. F., and Bredehoft, J. D., 1968, Application of the digital computer for aquifer evaluation: Water Resources Research, v. 4, no. 5, p. 1069-1093.

Prickett, T. A., and Lonnquist, C. G., 1971, Selected digital computer techniques for ground-water resource evaluation: Illinois State Water Survey Bull. 55, Urbana, Ill.

Texas Water Development Board, 1968, The Texas water plan: Texas Water Devel. Board planning rept.

_____1970, Systems simulation for management of a total water resource: Texas Water Devel. Board Rept. 118. Supplementary to Report 118 are seven computer program documentation volumes:

SIM-I Program Description (Multibasin Simulation and Optimization Model)
SIM-II Program Description (Improved Multibasin Simulation and Optimization Model)
Allocation Program Description
Stage Development Program Description
Data Management
Users Manual
Stochastic Demand Program

_____1971a, Simulation of water quality in streams and canals: Texas Water Devel. Board Report 128. Supplementary to Report 128 is the following volume:

QUAL-I Program Documentation and Users Manual (Stream Quality Model)

_____1971b, Stochastic optimization and simulation techniques for management of regional water resource systems: Texas Water Devel. Board Rept. 131. Supplementary to Report 131 are seven computer program documentation volumes:

SIM-III Program Description (Improved Multibasin Simulation and Optimization Model)
FILLIN-I Program Description (Hydrologic Data Fill-in Program)
AL-II Program Description (Improved Allocation Model)
DEMAND-II Program Description (Improved Irrigation Demand Model)
SEQUEN-I Program Description (Sequence Analysis Program)
CAPEX-I Program Description (Capacity Expansion Model)
Data Management and Analysis Program Description

_____1974, Economic optimization and simulation techniques for management of regional water resource systems: Texas Water Devel. Board Rept. 179. Supplementary to Report 179 are six computer program documentation volumes:

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

Young, G. K., and Pisano, W. C., 1968, Operational hydrology using residuals: Am. Soc. Civil Engineers Proc., Jour. Hydraulics Div., v. 94, no. HY4.