TEXAS WATER DEVELOPMENT BOARD

REPORT 118

SYSTEMS SIMULATION
FOR
MANAGEMENT OF A TOTAL WATER RESOURCE

A COMPLETION REPORT

VOLUME I INTRODUCTION

Prepared By
The Texas Water Development Board
And
Water Resources Engineers, Inc.

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 Interior, as authorized under the Water Resources Research Act of 1964 as amended.

May 1970
Second Printing, October 1970

Published and distributed
by the
Texas Water Development Board
Post Office Box 12386
Austin, Texas 78711

FOREWORD

This study was contracted for and partly funded by the Office of Water Resources Research, U.S. Department of Interior, an agency which is functionally structured to support needed water resources research and to insure the effective dissemination of research results to other areas where these results may have useful application or where related research may be planned or underway. Accordingly, this report has been addressed primarily to that funding agency, with a purpose of informing water resource planning administrators and staffs having interest in systems development and management.

The reader will note that the Abstract to this report lists a total of six volumes. This volume (Volume I) introduces the research and summarizes the pertinent findings; Volumes II through V contain supporting material and together with Volume I fully document the research. While much of this material is necessarily highly technical, we believe that Volume I will be of value and interest to the water planning administrator while all volumes will be useful to those researchers engaged in systems analysis and systems simulation studies. Volumes II through V will be available for reference in the offices of the Texas Water Development Board. Volume VI is administrative in nature and is not necessary to describe the research.

This research represents a first step towards developing a computer-oriented methodology for use in the planning, design, and long-range operation and management of a large, multi-basin water resource development program such as the proposed Texas Water System. The planning problem posed is how best to develop such a system, given the objective of meeting a predetermined demand for water for all purposes scheduled over a 50-year planning horizon. When should elements of the system be constructed and available for service? How large should reservoirs and canals be constructed? How much water should be imported? When? Where? How should the system be operated to meet the demand schedule at the lowest reasonable cost?

To provide the planner with an objective and reliable means for answering such questions, and for evaluating systematically the myriad of alternatives presented, the researchers drew on the techniques of the so-called "systems approach." Eight interrelated computer programs (four data management programs and four simulation/optimization programs) and a procedure for using these programs were developed.

The purpose of the data management programs is to provide the user with a convenient means for organizing most of the data required by the simulation/optimization programs. A detailed discussion of the data management programs and the types of data to be supplied as input to these programs is given in Chapter VII (pages 86-94).

The purposes of the simulation/optimization programs are to define: (1) when to construct proposed reservoir and transfer links, (2) what should be the maximum capacity of each of the reservoirs and transfer links, and (3) what should be the operating policy for the reservoirs and transfer links individually and collectively during and after the period in which facilities are being added so as to minimize the present worth of their construction costs, their operation costs, and their maintenance costs. A detailed discussion of the simulation/optimization programs is given in Chapters IV, V, and VI.

The procedure for using the simulation/optimization programs is presented in Chapter III. This procedure is divided into four distinct phases. The purposes of the first phase are to obtain an approximation of the sizes of the required reservoirs and canals and to obtain a good average operating scheme using the Allocation Program and the Volume Staging portion of the Stage Development Program. The purposes of the second phase are to select a large number of possible implementation plans (reservoir and canal construction times and capacities), evaluate each of these plans using a computationally inexpensive simulation program (SIM-I) in conjunction with the Stage Development Program, choose a few (e.g., five) plans on the basis of the values produced, and adjust the construction dates and capacities seeking to lower the present worth of the capital, operation, and maintenance costs. The purpose of the third phase is to further investigate two or three plans selected on the basis of phase two using a more detailed analysis program (SIM-II) which simulates as well as optimizes the operation of the reservoirs and canals on a monthly basis. As in phase two, the objective is to eliminate plans not worth further investigation and thus converge towards finding the plan having the lowest present worth. Phase four is a final screening step which is used to study only a limited number of plans identified in phase three and to isolate that unique plan which is the "best", using the Allocation Program (a more computationally expensive program but capable of optimizing over several years and thus finding lower-cost operating procedures).

In developing the system of programs described herein, a series of program specifications and their inherent assumptions were accepted. The resulting programs were designed to accomplish the minimum-cost objective function on a monthly basis using deterministic or synthetic sequences of reservoir inflow and net evaporation data, prespecified demands for water that must be met, and a planning period of not-to-exceed 50 years. They are also designed to permit reservoirs and pump-canals to be added to the network at yearly intervals. Worthy of note are items which the programs cannot evaluate. They will not treat more than one source of import water in a single analysis; nor treat water quality parameters explicitly; nor analyze conjunctive use of ground water and surface water unless the ground water source is treated as a retention reservoir with a pump-canal connecting it to the surface network. Although a buildup of demands, with respect to time, can be analyzed, incremental staging of individual reservoir and canal sizes cannot be handled in a single run; however, by making successive analyses at various points on the demand buildup curve, reservoirs and canals can be optimally sized at each point, and thus, incrementally staged.

The procedure for using the simulation and optimization programs was tested on a case study (a portion of the Texas Water System) comprised of a network of 18 reservoirs, 30 interconnecting canals, 12 river reaches, and 24 demand points spanning about 500 miles across the State of Texas. The procedure was found to be sound, and was carried out at a reasonable manpower and computational cost. Mathematically speaking, the procedure cannot guarantee selection of the absolute minimum-cost solution; however, it does give the planner a method of evaluating many alternatives in an organized manner, thus greatly increasing the probability that the finally selected plan will represent the lowest cost possible. The procedure can also be used to evaluate the sensitivity of both the capital and operation costs to modifications in the finally selected plan and various imposed operation criteria.

A more detailed discussion of the conclusions reached and the recommendations for follow-on activities are presented in Chapter I (pages 1-5). Briefly the report concludes that although the procedure has produced reasonable results in the test case study, it has not been used in the formulation of an actual plan for implementation. This formulation, along with a project designed to improve the computational efficiency of the programs, is scheduled in the near future. Considerable follow-on testing and application are sure to identify needed improvements both in the individual models and in the application procedure. One specific weakness is in the rigidity of the operating rules (discussed on pages 32-34); another is the inability to incrementally stage the size of a pump-canal over the simulation period. The need for modifications in these areas does not, in the opinion of the researchers, necessarily detract from the usefulness of the existing programs and the methods of program application described herein. Thus, the researchers believe that the results of this research can now be applied to planning situations and problems with modifications where necessary.

The size of networks that the procedure can treat is necessarily constrained by the capacity of the computer available and its computational speed. Realistically, a network of up to 30 reservoirs and/or canal junctions, 45 canal links, and 600 time increments (months) can be analyzed with the existing computer code and approximately 60,000 words of computer core storage. With slight modifications of the computer code even larger systems could be analyzed.

This procedure is best suited to large networks comparable to the one used in the case study. The simplest system that can be analyzed is a single reservoir; however, a system of at least two reservoirs and an interconnecting river reach or pump-canal should exist before the use of the procedure becomes practical.

PREFACE

Background

In response to an intra-agency need, the Texas Water Development Board has embarked upon a long-range program of applied research in water resource system simulation and optimization. The general objective of this research is to develop a generalized computer-oriented planning system that can be used in the detailed planning, design, and management of water resource systems such as the Texas Water System, which is part of the overall Texas Water Plan.

With the financial and consultative assistance of the United States Department of Interior, Office of Water Resources Research, the guidance of an eminent research advisory panel, and the technical support of Water Resources Engineers, Inc. (WRE) of Walnut Creek, California, the Texas Water Development Board has completed the first phase of the research program. This volume summarizes the results of this effort, the primary objective of which was to develop practical simulation and optimization techniques capable of being used by planning agencies in the actual analysis of water resource planning problems.

Organization

The Texas Water Development Board was responsible for overall project management, under the general direction of Mr. Lewis B. Seward, Assistant Chief Engineer for Planning. Mrs. Jean O. Williams, Program Controller and Mr. John J. Vandertulip, former Chief Engineer, along with Mr. Seward, were instrumental in the early conceptual planning of this project and in establishing and maintaining liaison with the Office of Water Resources Research.

The newly formed Systems Engineering Group, comprised of Mr. Joe C. Moseley and Mr. Carlos Puentes, under the direction of Mr. Arden O. Weiss carried out the Board's technical responsibilities. These responsibilities included formation of a data base, the development, programming, and debugging of the data management programs, and writing portions of the Completion Report.

Dr. Wilbur L. Meier, Associate Professor at Texas A&M University, served as Co-Principal Investigator with Mr. Weiss and assisted the Board in the formulation of its Systems Engineering Applied Research Program.

Water Resources Engineers, Inc., under the direction of its president, Dr. Gerald T. Orlob, assumed responsibility for the modeling aspects of the project, devising a solution methodology, developing the necessary computer programs, debugging and implementing these, and writing portions of the Completion Report. Mr. Donald E. Evenson was Project Leader for the Water Resources Engineers, Inc. team working in Austin and assumed specific responsibility for the development of the Allocation Program. Dr. George K. Young was responsible for devising the Stage Development Program while the Simulation Programs were created by Dr. W. D. McMillan, Mr. William R. Norton, and Mr. Larry S. Costello.

Acknowledgments

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

First, the research team wishes to acknowledge the enthusiastic support given the project by the Texas Water Development Board, its members individually, and its Executive Director, Mr. Howard B. Boswell.

Special acknowledgment is due the Office of Water Resources Research for its unique expression of confidence in the research concept. The advice and encouragement given by Dr. Roland R. Renne, former Director, Mr. Eugene D. Eaton, Associate Director, and Dr. Edward G. Altouney, Research Scientist, are much appreciated. Likewise, we are grateful for the continued interest and support of this research by the encumbent director Dr. H. Garland Hershey.

The researchers are deeply appreciative of the contribution received from the Consulting Panel; Mr. Dean F. Peterson, Chairman, Mr. Harvey O. Banks, Mr. Leo R. Beard, Dr. Ven Te Chow, and Dr. Allen V. Kneese. Throughout the project they reviewed progress and gave invaluable guidance to the research staff.

Dr. Paul A. Jensen, Assistant Professor at The University of Texas at Austin, is deserving special recognition for making available to the Board the optimization technique used in both SIM-II and the Allocation Program, and for providing consultive assistance in its use.

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

ABSTRACT

Systems Simulation for Management of a Total Water Resource.

Texas Water Development Board, Austin, Texas

Water Resources Engineers, Inc., Walnut Creek, California

Office of Water Resources Research, Washington, D. C.

File Retrieval Descriptors:

PLANNING Water Resources Development, Optimum Development Plans (Minimum Cost), Model Studies, Hydrologic Models, Computer Models.

OPERATIONS RESEARCH Systems Analysis, Networks, Simulation, Optimization (Minimum Cost), Linear Programming, Sampling.

This research represents a first step towards the development of a computer-oriented planning system for use in the planning of large, multi-basin systems of reservoirs and connecting transfer links (river reaches and pump-canals) such as the proposed Texas Water System. Eight interrelated computer programs (four data management programs and four simulation/optimization programs) and an approach for using these programs were developed. This research has also resulted in the development of a program to generate stochastic demands for irrigation water.

The purpose of the data management programs is to provide the user with a convenient means for organizing, in the proper form, most of the data required by the simulation/optimization programs.

The purpose of the simulation/optimization programs is to collectively define (1) when to construct proposed reservoirs and transfer links, (2) what should be the maximum capacity of each of the reservoirs and transfer links, and (3) what should be the operating policy for each of the reservoirs and transfer links, both during and after the period in which facilities are being added, to minimize the present worth of their construction costs, their operation costs, and their maintenance costs.

The programs are designed to accomplish these purposes on a monthly basis using deterministic or synthetic hydrology, pre-specified demands for water that must be met, and a planning period of not-to-exceed 50 years.

This research is documented in the following volumes:

Volume I – Introduction
Volume IIA – SIM-I Program Description
Volume IIB – SIM-II Program Description
Volume IIC – Allocation Program Description
Volume IID – Stage Development Program Description
Volume III – Data Management
Volume IV – Users Manual
Volume V – Stochastic Demand Program
Volume VI – Research Accomplishment and Cost Summary

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SYSTEMS SIMULATION FOR MANAGEMENT OF A TOTAL WATER RESOURCE

A Completion Report

I. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

As available water and land resources diminish and demands for them increase, the objectives of water resource planning broaden, the physical facilities required become more complex, and the limitations under which they must be implemented become more stringent. There exists a rising and urgent need to utilize to the fullest advanced techniques and tools which can enhance the capability of the planners to make the necessary decisions concerning the configuration of major water resource systems and when each significant element should be placed in service. Because costs for construction, operation, and maintenance of facilities and for the purchase of water and energy to pump it are likely to be large, the means must be found for finding solutions which are both practical and economical.

The research project which is described in this report is an attempt to develop and apply some new and existing techniques to the planning of complex water and related land resource systems. It was performed using, as a case study, the Trans-Texas Division of the Texas Water System, a system of major proportions that involves many reservoirs, canals, and pumping facilities spanning the State of Texas. The planning problem posed was how best to develop such a system, given the necessity to meet a predetermined water-demand schedule over a 50-year planning horizon. When should elements of the system be constructed and available for service? How large should reservoirs and canals be constructed? How much water should be imported? When? Where? How should the system be operated during the course of implementation to meet the demands at the lowest reasonable cost?

To provide the planner with some objective and reliable means for answering such questions and for investigating systematically the myriad alternatives presented, the researchers drew on the techniques of the so-called "systems approach." Four specialized computer programs were designed and utilized as integral components of a screening procedure which was devised to follow the planner's logic.

The *Stage Development Program* is an optimization procedure designed to estimate the best schedule for implementation of various elements of a complex system. It seeks the least costly alternative by sampling the cost "response surface" and improving systematically on choices which are close to minima.

Simulation Program I, or SIM-I, is utilized to describe the hydraulic behavior of the system as development proceeds over the planning horizon and to estimate the costs associated with storage, conveyance, and purchase of water. It solves a set of simultaneous equations derived from mass balances about each node (reservoir or non-storage junction) in a simplified tree-shaped system of nodes and connecting links (canals or river reaches).

Simulation Program II, or SIM-II, is an optimization technique which utilizes the so-called Out-of-Kilter Algorithm to find the least costly pattern of operation for the system as it is expected to evolve over the planning period. It allows the planner to consider a wider range of system configurations, including those which include "loops" and to explore the consequences of imposing size or operating constraints on the system.

The *Allocation Program* is a formal means for solving for the "optimum." It also uses the Out-of-Kilter Algorithm to find the least costly way of satisfying demands over the planning horizon, and it can be employed to estimate operating rules and to size elements of the system.

The screening procedure which uses these four programs is divided into four distinct phases, as shown schematically in Figure 1. It is initiated with certain information on the configuration of the ultimate system, including potential reservoir sites and canal routes. Estimates of future demands are presumed to be available and the hydrologic conditions of supply are determined.

The initial phase of screening entails preliminary sizing of canals in the ultimate system. This is accomplished using the Allocation Program to find the lowest annual cost of canal construction and operation under the stipulated conditions. An "unconstrained" solution produces maximum flows in canals. These are then constrained to more realistic values in accord with

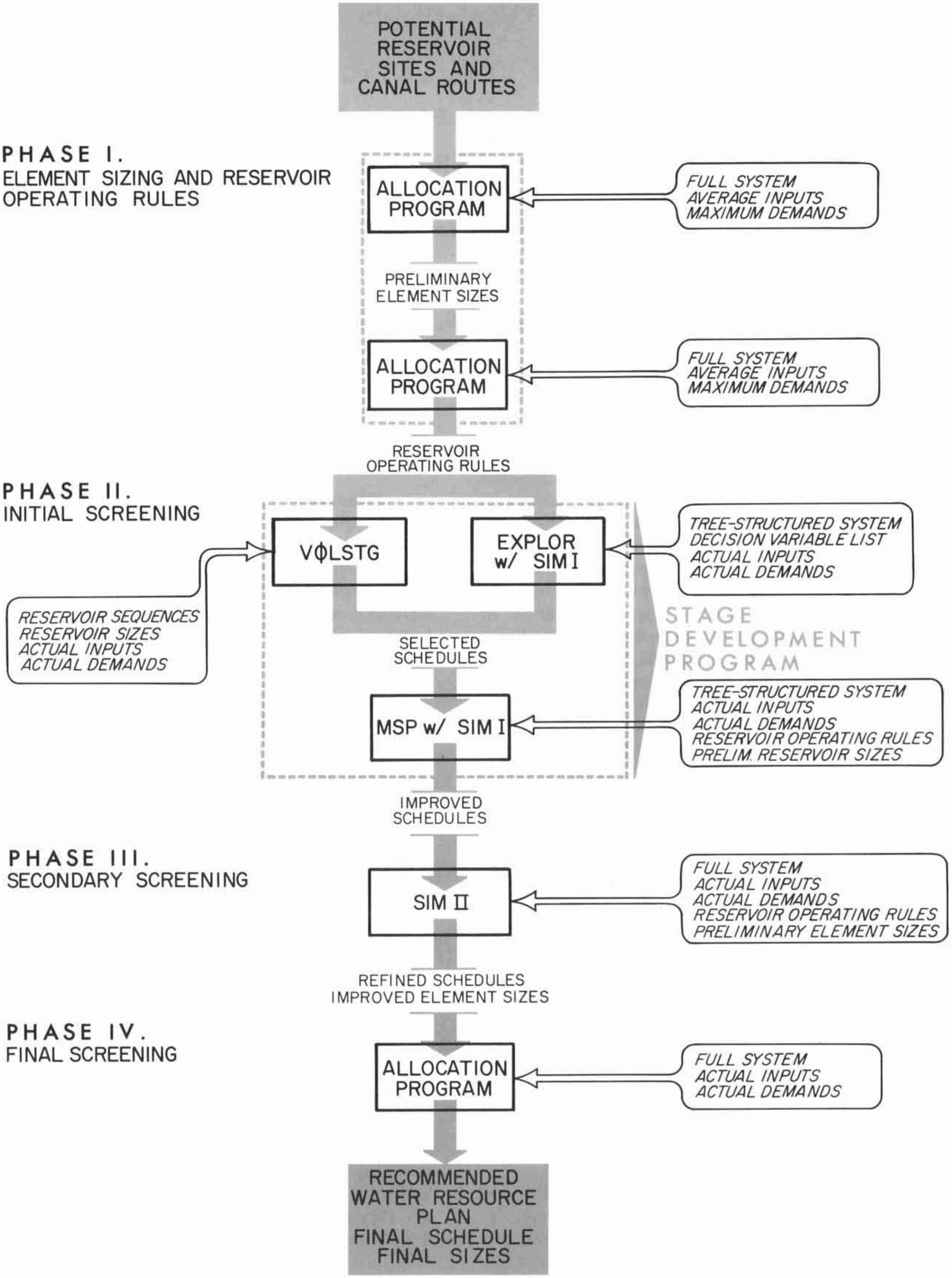

Figure 1

SCHEMATIC REPRESENTATION OF THE FOUR PLANNING PHASES planning judgments with a view to reducing flow variability in individual elements of the system and driving costs downward. Marginal costs of capital and energy, revealed by the solution, are used to guide the imposition of constraints. The process is essentially trial and error and is terminated when, in the judgment of the planner, no further cost improvement can be achieved.

The Allocation Program is also employed in the first phase of the planning process to estimate rules for reservoir operation. These rules, which relate the content of an individual reservoir to that of the system as a whole, are used subsequently in SIM-I and SIM-II. They are based on the ultimate system configuration, preliminary element sizes, and average demands and hydrology.

Phase II of the planning sequence, Initial Screening, employs the State Development Program. Selected schedules for placing system elements in service are developed by either of two subroutines, Volume Staging (VOLSTG) or Random Sampling (EXPLOR). These alternative schedules are improved on by another subroutine, the Method of Successive Perturbations (MSP). Successive iterations in the schedule are performed with the aim of driving the search toward minima on the response surface. SIM-I, applied over the full planning horizon, is used to evaluate system performance and estimate costs.

The best schedules of system implementation are carried forward to Phase III, Secondary Screening. SIM-II is used to refine the schedule and to improve element sizes.

Final Screening, Phase IV, entails application of the Allocation Program to the full system, implemented according to the refined schedule from Phase III. Actual inputs and demands over the planning horizon are used and constraints are imposed in accord with planning judgments. A recommended water resource development plan, including a final schedule for implementation and the sizes of system elements, emerges as the final product of this phase.

The planning sequence outlined above and the programs developed were tested in a case study of the Trans-Texas Division of the Texas Water Plan. The test system consisted of a network of 18 reservoirs, 30 canals, and 12 river reaches spanning about 500 miles across the State of Texas. Nine of the reservoirs were considered to be in place by 1985 when a reallocation of in-state water resources would have to begin; the remaining nine were to be scheduled over the ensuing 36-year period. Hydrologic conditions were derived from a 17-year historic record, and demand schedules were those contemplated under the Texas Water Plan.

The effectiveness of the planning techniques and programs is best measured in terms of their capabilities to improve on the design of a complex water resource system, i.e., to reduce cost while meeting fixed goals of demand, and dependability of operation. The first estimates of system cost, including penalties for deficits incurred in operation over the 36-year planning period, obtained by SIM-I in Phase II, ranged upward from $6.31 billion. These were for the tree-shaped system configuration required by SIM-I, sized and operated according to the criteria developed by a preliminary application of the Allocation Program. The Method of Successive Perturbations was used successfully to reduce the cost of the "best" alternative to $6.07 billion by modifying the proposed implementation schedule.

In the succeeding phase of the test problem, SIM-II was applied to the system, with looping permitted and the schedule as predetermined. An "unconstrained" solution, i.e., no flow limits on canals, resulted in a cost of $7.15 billion, but this was reduced after two adjustments of canal sizes to $5.93 billion.

An initial application of the Allocation Program in the final screening phase was used to identify the causes of a deficit which had been anticipated in an earlier application of SIM-I. A slight rescheduling of two system elements resulted in removing the deficit condition and the program was applied successfully over a 23-year period, including the 12-year implementation schedule. The run was terminated in the last year of an 8-year drought, and sufficient data were secured to provide reliable estimates of component costs for the entire 36-year period. The alternative plan was estimated to cost a total of $4.60 billion. This reduced cost was achieved primarily through smaller canal sizes.

The present worth of alternative development plans as computed by SIM-I, SIM-II, and the Allocation Program is summarized by component costs in Table 1.

Table 1.—Present Worth of Alternative Development Plans as Computed by SIM-I, SIM-II, and the Allocation Program (Billions of Dollars)

COMPONENT	PROGRAM		
	SIM-I	SIM-II	ALLOCATION
Reservoirs	0.52	0.52	0.52
Canals	4.21	4.00	2.90
Power	1.20	1.13	1.11
Imports	0.14	0.28	0.07
Total	6.07	5.93	4.60

Conclusions

The research reported herein resulted in the development of a specific new methodology for planning complex water resource systems, utilizing some advanced techniques of the so-called "systems approach." The significant conclusions of the research are:

> *The approach, developed and tested in this research, for the screening of alternative water resource development plans, is feasible.*

The approach is technologically workable and can be carried out at reasonable cost. However, it cannot guarantee selection of the minimum-cost solution; it can only increase the likelihood of finding it by greatly expanding the potential of the informed planner to make "good" decisions. While it has been tested on one real system, the methodology is not completely perfected. Future development effort will be needed to insure its continuing viability in water resources planning.

> *The techniques and tools used in the approach are comparatively new to the field of water resources planning and have not previously been successfully applied to systems as large and complex as that of the Trans-Texas Division of the Texas Water Plan.*

Although the techniques have been shown to produce reasonable results in a test case study of the Texas Water System, they have not yet been used in the formulation of an actual plan for implementation. It will be necessary in future studies to make this transition to practical application. Moreover, it will be essential, if the techniques are to be of wide utility, to expand them to treat the economic consequences of such considerations as power generation, recreation, flood control, water quality management, and conservation.

> *The Stage Development Program, in combination with a reliable simulator, is an efficient means for preliminary screening of alternative development plans.*

The program has the capability to generate large numbers of alternative schedules for implementation to simulate performance, to develop cost information, and to improve on costs in a systematic manner. It can eliminate rapidly, and at nominal cost, large numbers of infeasible solutions and direct attention to those which are sufficiently attractive to warrant further refinement.

> *Simulation Program I, SIM-I, is an efficient simulator for systems of canals and reservoirs which can be represented in a "tree-shaped" structure.*

It utilizes fixed operating rules derived from deterministic hydrology and predetermined demands. Because loops are not permitted, SIM-I may predict conditions which cannot occur in the prototype. This apparent disadvantage may be used in preliminary stages of planning as a diagnostic for the reasonableness of alternative system configurations.

> *Simulation Program II, SIM-II, provides a realistic means for simulation and optimization of complex systems where flows may be limited in either direction or magnitude, or where loops are necessary to represent real conditions.*

SIM-II's reliance on predetermined operating rules is a shortcoming that needs to be corrected. The cost of operation of this highly flexible simulator could also be reduced from its present level. Running time is presently 30 to 50 times as long as for a comparable problem with SIM-I.

> *The Allocation Program, a true optimization procedure using the Out-of-Kilter Algorithm, is an effective tool for exploring the sensitivities of cost to element sizes, developing operating rules, and simulating optimum system operation.*

Running times are relatively high, 20 to 30 times greater than for SIM-II; hence, use of the Allocation Program must be limited to alternatives which have survived the earlier phases of the screening processes.

Recommendations

It is recommended that the approach conceived and preliminarily tested in this research be further developed and refined, and that it be brought to bear as soon as practical on the real problems of water resource planning.

An initial step toward development of the desired refinement in methodology is to conduct an organized program of sensitivity testing. A second is to institute procedures for training of planners in the use of the approach and the specific techniques it embraces. Finally, in order to reveal its capabilities and limitations, it is essential that the approach be applied, not only to the Texas Water System, but to other complex water resource systems. The following are specific recommendations in each of these areas of concern.

Sensitivity Analysis

A decision between alternatives generally presupposes knowledge of the factors that influence the choice. Among the factors to which the decision process in water resources planning is sensitive are the analytical techniques themselves, certain variables and assumptions which characterize them, and input data.

It is recommended that, for the approach developed in this research, at least the following be explored:

- sensitivity of the Stage Development Program to the structure and accuracy of the simulation program(s) employed;
- sensitivity of the Method of Successive Perturbations to the structure of the initial implementation plan;
- sensitivity of SIM-I and SIM-II to hydrologic conditions, demand projections, and reservoir operating rules;
- sensitivity of the Allocation Program to assumptions concerning evaporation losses and the constancy of pumping lifts; and,
- sensitivity of results of each decision level of the planning process to hydrologic and demand data.

Other Applications

The recommended approach can best be improved by use on actual planning problems. It is recommended that other systems be studied using the approach devised in this research, adapted as need be to cope with special problems. Other subsystems of the Texas Water System are likely candidates, with variations which would challenge the capabilities of the techniques already developed. The approach should be extended to encompass evaluation of systems in which costs are identified with the functions of power generation, flood control, recreation, water quality control, and conservation. Capability should be provided to deal with the more complex problems of staging the construction of pumping facilities and canals.

II. WATER RESOURCE PLANNING

As available water and land resources[1] dwindle and demands for them mount, the objectives of water resource planning become broader, the physical facilities become more complex, and the constraints within which water resource systems must be implemented become more stringent. The purposes of this introductory chapter are: (1) to describe how these changes are making water resource planning more difficult, (2) to cite the Texas Water Plan as an example, and (3) to establish the need for better analytical techniques to enhance the water resource planner's capabilities to cope with these problems. Development of these techniques is only in the initial state. The research efforts reported herein hopefully will contribute to the satisfaction of these needs.

The Planning Process

Planning is the process by which society directs its activities to achieve goals it regards as important. Primary goals are to determine what physical facilities must be constructed and to determine a schedule for their implementation and operation that will assure satisfaction of anticipated water demands in the most effective and economic manner within the constraints imposed.

The planning process must be capable of evaluating alternative measures for reaching these goals and answering a wide range of "what if" type questions posed by water resource planners, design engineers, and those individuals and organizations concerned with the results of the planning process. Where available water resources are marginal in quantity or scarce with respect to possible demands and the competition among various users is great, the problem of defining objectives and formulating a system to meet those objectives becomes increasingly difficult. It tends to be focused more sharply on the proper allocation of limited resources among competing and conflicting demands. Considerations of maximum net benefit to the users of the resource often guide the planner as he seeks that plan which is to be recommended.

The planning process must give full consideration to implementation of the resultant water resource plan, including institutional arrangements, financing, and repayment. Unique problems of design and of operation and management must also be recognized.

Planning is accomplished through a logical and systematic evaluation of alternatives, considering:

- the *objectives* of water resource planning,
- the *constraints,* social, economical, and political, that are imposed on the planning process,
- the *beneficial uses* of water and related land resources,
- the *resources available* to satisfy user requirements,
- the *physical facilities* needed to develop the resources and make them available for use,
- the *implementation* of the water resource system, and
- the *operation* of the physical system in an efficient manner.

Planning Objectives

A recently released task force report (Steele, 1969) to the Water Resources Council on procedures for evaluation of water and related land resource projects lists the national objectives for water resource development as:

- national Income,
- regional Development,
- environmental Enhancement, and
- well-Being of People.

The task force, composed of staff members of the U.S. Departments of Agriculture, Army, and Interior, and of the Water Resources Council, suggests that these objectives:

> *...provide the framework within which the effects of water and related land projects may be evaluated.*

The task force report states further:

> *National income measures the Nation's output as the aggregate earnings of labor and property which arise from current and future production.*

---

[1] In this report, "water resource systems" is considered to include all related land resources.

> *The increase in national income attributable to a project or plan is the measure of its contribution to this objective. These gains result from provision of water supplies for domestic, municipal, agricultural, and industrial uses; water quality control; navigation facilities; flood control; land stabilization; drainage; watershed protection; and outdoor recreation and fish and wildlife opportunities.*
>
> *The regional development objectives embrace several related components such as (1) increased regional income, (2) increased regional employment, (3) improved regional economic base, (4) improved income distribution within the region, and (5) improved quality of services within the region.*
>
> *Environmental objectives include the conservation, preservation, creation, or restoration of natural, scenic, and cultural resources in order to enhance or maintain the quality of the environment.*
>
> *...well-being objectives consider the personal, group, and community effects of the project or program activity. Since some of these well-being objectives have a location impact, there is a close relation to regional development objectives. Included are such objectives as security of life and health, national defense, personal income distribution, and inter-regional employment and population distribution.*

These objectives will become of greatest concern to the planner when the contemplated water resource systems involve large regions and a high degree of national interest. Systems designed to fulfill only local interest may have more limited objectives, such as the minimization of project costs or the maximization of local net benefits. Regardless of the size or scope of the system, the planner must clearly state and define, in advance of planning and system formulation, the objectives that are proposed to be met. Only then can he proceed to evaluate systematically and objectively the various courses of action open to him and to make the critical decisions about which alternative best satisfies the stated objective.

Constraints

Legal constraints are probably the most significant ones imposed by society. These include interstate compacts, legally recognized water rights, and priorities of use for particular areas, such as the County of Origin Act and Watershed Protection Law of California. Administrative policies that stem from these statutes impose further constraints. Cases in point are the "clean water" policy expressed in the Federal Water Pollution Act as amended, policies of the Secretary of Interior for the implementation of this act, and the land utilization objectives and repayment policies of the Reclamation Act of 1902 and supplementary and amendatory acts thereto.

In many states, including Texas, water agencies of various types already exist and legislatures have accorded to these agencies broad authority over the development and utilization of water and related land resources within their boundaries. Many such agencies have already stated their objectives and formulated plans to meet them. In the formulation of large-scale systems that cover broad areas, all such plans must be given full consideration.

In most river basins and the regions they serve, there are existing or authorized Federal, State, and local projects which must be incorporated, to the extent possible, into new systems being planned. The contractual operating commitments and the commitments to those who have purchased the bonds to finance construction of such facilities must be honored or other arrangements made. The availability of financial resources, which are generally limited, to implement water resource plans is also a significant constraint.

Finally, public attitudes are important in water resource planning. The current public concern over ecological and environmental effects of water development projects is having a major impact upon the planning process.

Water Uses

The uses of water resources may be categorized as (a) direct use of water and water resources for human needs, (b) uses necessary to develop and make other resources available, and (c) other benefits achieved through water development. These uses are not as clearly distinguishable as they appear from this relatively simple categorization. In the evaluation of uses, full consideration must be given to ecological and environmental inputs and impacts, as well as the effects of return flows from use of the water resource.

Direct uses include:

- domestic use,

- municipal use (exclusive of industrial use from municipal systems),
- use for final disposal of treated municipal wastes and urban runoff,
- recreation, and
- hydropower generation.

The uses of water for the development of other resources include:

- industrial uses (including cooling),
- irrigation,
- maintenance of fish and wildlife resources,
- mining and oil production,
- navigation, and
- use for final disposal of treated industrial wastes, including waste heat, and agricultural drainage.

A major portion of the total use of water resources is involved in making available or utilizing other resources, particularly land resources, to meet human needs.

A number of other direct benefits stem from water resource development; these include flood protection and water quality control. Water quality requirements for these many uses vary widely, and these requirements must be fully taken into account in the planning process. As water uses increase, both in variety and number, it is necessary to plan for and manage conjunctively water quantity and quality.

Water Resources

The total water resources consist of:

- surface water resources, including dam and reservoir sites,
- underground resources, which include not only ground water but also underground storage capacity and transmission capability,
- atmospheric waters (The amount of surface water available in the future may be increased by weather modification),
- return flows or waste waters, and
- saline or brackish waters.

Surface water, ground water, atmospheric waters, and return flows are highly interrelated. The amounts of surface water and ground water available vary widely over time and space; this is due not only to natural causes but also to such other factors as the level of resource development and land treatment and use. The planner must relate both the quantity and the quality of these resources to the requirements of the water users to successfully meet his stated objectives.

Physical Facilities

To support these needs with the available resources and within the recognized constraints, systems of physical facilities have become much more complex; they have progressed from single or dual purpose projects involving simple works to multi-facility projects serving several purposes over wide geographical areas. The physical facilities involved in these complex systems may by extensive and include such diverse facilities as:

Dams and reservoirs
Canals and other types of conveyance works
Pumping plants, including energy sources
Hydropower plants
Wells
Artificial recharge works
Distribution systems
Water treatment plants
Waste water treatment plants
Waste water reclamation plants
Channel improvements
Flood retardation facilities
Land treatment measures for runoff and erosion control
Weather modification facilities.

Many regional systems of the future will probably encompass most, if not all, of these facilities as well as some that are not listed. These must be planned, designed, and operated conjunctively to develop the resources, to meet the demands, and to accomplish the objectives.

Complex water and related land resource systems may and probably will encompass the facilities financed, designed, and operated by both private and governmental entities. Institutional arrangements among the varied interests for financing, designing, operating, and managing such systems are necessary.

These extensive regional systems will normally be very complex; they will draw water from diverse sources—surface, underground, desalted, and reclaimed water—and they will be operated as integrated systems. At the same time, demands will increase while the constraints imposed, legal and otherwise, will become more limiting. The planner will have to give more attention to ecological and environmental impacts, both beneficial and detrimental. As a consequence, the alternatives he will have to consider to plan, to design, and to operate these complex systems will greatly increase. The Texas Water Plan is an example of such a complex system.

The Texas Water Plan—An Example

The use of a real problem to provide the framework to test, evaluate, and verify the methodologies developed in an applied research program is basic to its success. The purpose of this section is to discuss a water resource problem that now faces the Texas Water Development Board. This problem, in the abstract, is similar to the problem that the California Department of Water Resources first faced several years ago and that water resources planners, in increasing numbers, throughout the world will face in the future.

History

Acting under the stimulus of a prolonged drought, broken by heavy rains and flooding in the Spring of 1957, the Texas State Legislature in special session adopted the Water Planning Act of 1957. Complying with provisions of that Act, the Texas Board of Water Engineers[2] prepared and submitted to the Legislature the following year a progress report entitled "Texas Water Resources Planning at the End of the Year 1958."

In May of 1960, Governor Price Daniel requested that the Board of Water Engineers assume State leadership to coordinate water planning in Texas, and to prepare a statewide plan to meet municipal and industrial water requirements. In cooperation with river authorities and cities, the Board prepared, in May of 1961, a report entitled "A Plan for Meeting the 1980 Water Requirements of Texas."

The Congress of the United States, by Congressional Act of August 28, 1958, authorized the United States Study Commission-Texas. It was commissioned to formulate a basic, comprehensive, and integrated plan for development of the land and water resources for a defined study area, which included only about 62 percent of the State of Texas.

The U.S. Bureau of Reclamation and the U.S. Army Corps of Engineers subsequently completed several reports on specific projects. The Corps of Engineers reports described multiple-purpose reservoir projects, local flood control, navigation (primarily along the Texas Gulf Coast), hurricane protection, and comprehensive studies of the Sabine and Trinity River Basins. The Bureau of Reclamation completed its Preliminary Report on the Texas Basins Project in 1963, a plan to redistribute intra-state surplus waters.

Local entities—cities, river authorities, and water districts—also suggested projects in their areas, some of which conflicted with the proposals of the Federal agencies.

Governor John Connally recognized the need for a more orderly and longer range analysis of the State's water problems, water needs, and solutions to these problems, and by letter to the Texas Water Commission[2] dated August 12, 1964, he requested that a comprehensive State Water Plan be prepared. He said:

> *I am increasingly concerned about drought conditions in Texas and progress of our efforts to develop adequate sources of water for all our State. I'm sure the members of the Texas Water Commission share this concern with all our citizens.*
>
> *The Bureau of Reclamation and the Corps of Engineers have proposed broad water development projects for Texas far beyond the plans of the Texas Water Commission report, "A Plan for Meeting the 1980 Water Requirements of Texas." In my opinion, these plans fall short of satisfying the water needs for all of Texas.*
>
> *Furthermore, the Congress is presently considering a Federal water pollution control bill which will supplant state authority in this field. I have long been concerned that the State exercise its responsibility in all areas of water conservation and development. The recently enacted Water Resources Act of 1964 does provide an opportunity for state participation in federal water research programs.*
>
> *As you know, it is my responsibility, with the help of the Texas Water Commission, to review major federal projects and formally approve or disapprove them on behalf of the State. I*

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[2] The Texas Board of Water Engineers was renamed the Texas Water Commission January 30, 1962. On September 1, 1965, the water-development planning functions of that agency were realigned in the present Texas Water Development Board.

> *cannot properly evaluate some proposed federal projects without a longer-range State Water Plan for Texas.*
>
> *Therefore, by authority granted me under Article V, Section 22, House Bill 86, 58th Texas Legislature (The General Appropriations Act), I hereby request the Texas Water Commission to use any available monies appropriated under the Act to begin at once to develop a comprehensive State Water Plan. 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 preliminary reports of the federal agencies.*

Current Status of Planning

At present, planning has proceeded from the request of the Governor in 1964 to the adoption by the Texas Water Development Board in early 1969 of the Texas Water Plan—a flexible guide for the orderly development, conservation, and management of the State's water and related land resources to meet the needs of the people of Texas to the year 2020.

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

Other major concepts (Boswell, 1968) which *constrain* the plan, include:

(1) *The plan is a flexible guide to the development of the State's water resources. The Plan must be flexible if it is to meet changing conditions.*

(2) *The Plan is based on the premise of no interference with vested rights, including the protection of in-basin water rights.*

(3) *Implementation of the Plan will be a coordinated and cooperative effort of the Federal Government, the State, and political subdivisions of the State.*

(4) *In general, water basin sources, sites, and facilities are to be developed on a multipurpose basis.*

(5) *Adequate inflows of fresh water will be provided for the bays and estuaries.*

(6) *Maximum assistance of the Federal Government and its agencies will be sought, but water users will be expected to pay most of the costs of development of the water resources.*

Estimates of water *demands* were made using conventional methods for projections of economic development, population growth, and of the future of irrigated agriculture. Water requirements for municipal and industrial use and for irrigation were based on average unit values.

The Board estimated the available *water resources*, basing the firm yields of reservoirs on modified runoff records with each reservoir considered separately. Estimates of return flows also were developed. The Board recently initiated studies to develop the information needed to formulate plans for conjunctive operation of surface and underground water resources, particularly in the High Plains of West Texas.

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

The general nature and locations of the physical facilities required have been determined with reasonable certainty. However, the sizes, sequencing, and staging of the many physical elements have not yet been determined except as rough approximations. The major facilities of the Plan include:

- the Texas Water System,
- interstate system (import and export),
- projects to meet local requirements, and
- facilities for purposes other than water supply.

To provide an example problem for use in the research described in this report, the Board selected the Trans-Texas Division of the Texas Water System; it is shown in red in Figure 2 and described more fully in Chapter VIII.

Future Planning Problems

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

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

- The estimates of future water demands for the several uses must be refined. Better estimates of the extent and pattern of future economic development, of population growth and distribution, and of unit water demands are essential. Detailed studies of the hydrology, hydraulics, biology, and ecology, and of the uses to be made of the bays and estuaries, are required to quantify the amounts and regimen of the necessary fresh water inflows. Since the demands for irrigation in the High Plains of West Texas, which is the largest single demand on the system, are dependent, to a significant degree, on rainfall, they must be analyzed on a probabilistic basis. A tolerable risk of shortage must be estimated.

- A more thorough analysis of the resources available—surface, underground, and return flows—is needed. Surface water resources must be subjected to stochastic analysis to obtain better estimates of the amounts of surface water that will be available. This must be done not only on an individual river basin basis, but also in combinations of river basins with different hydrologic characteristics.

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

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

- Operational criteria for the Plan must be developed.

- Institutional arrangements for the operation of the Plan must be made.

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

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

Need for Advanced Planning Techniques

The planning concepts and the analytical techniques available today are inadequate to plan and formulate complex water and related land resource systems such as the Texas Water System. It may never be possible to take all the many variables, inputs, and outputs fully into account in a wholly logical and systematic manner. Assumptions and simplifications will continue to be necessary. Nonetheless, full application of the "systems approach" will provide water resource planners with a more improved set of tools than is now available.

The research project described in this report is an attempt to develop and apply new and existing techniques in the planning of complex water and related land resource systems. These techniques are particularly useful in an analysis of physical systems that involve several interconnected reservoirs, extensive pumped conveyance works, and terminal storage, and that serve several uses. Chapter III contains a detailed description of the problem investigated and the approach used to solve it.

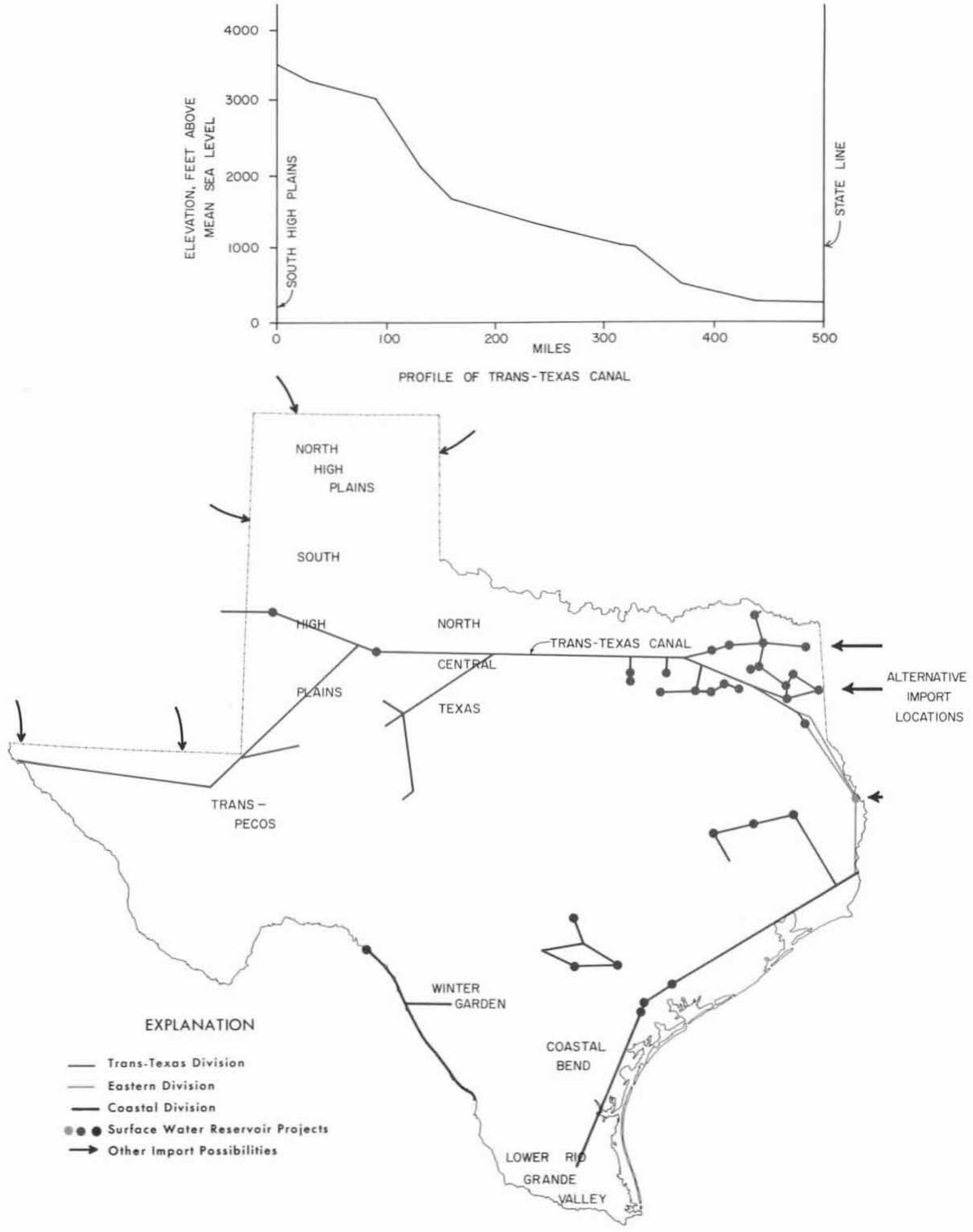

Figure 2

SCHEMATIC DIAGRAM OF THE TEXAS WATER SYSTEM

(Includes major conveyance facilities and related reservoirs)

III. THE PROBLEM AND AN APPROACH

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

This chapter describes the objectives of the research effort as presented to the OWRR, the specific planning problems posed by the proposed Trans-Texas Division, and the approach adopted as most promising for achieving a solution which will be of general utility in planning activities.

Research Objectives

The general objective of the research effort, as stated in the Board's proposal to the Office of Water Resources Research[3], was:

> *...to develop techniques and solution methods applicable to major water resource management operations by use as a case study the Trans-Texas Division of the planned Texas Water System as an aid in determining the least costly means of supplying municipal, industrial, irrigation, and secondary recovery (petroleum) water requirements to be served by this Division to the year 2020. A methodology will be sought to aid planners in formulating recommendations as to the allocation of water (within the constraints applicable to any point in time, i.e., firm water sales contracts, statutory priorities, etc.) and the physical sizing and timing of individual facilities of the division.*

The techniques that evolved from this investigation are not intended to be case-specific, but rather they are to be applicable to a fairly wide range of planning situations, many of which are exemplified by the Trans-Texas Division. Among the more importnat planning needs identified for the Trans-Texas Division system are capabilities for (1) simulating the system's behavior under alternative operational plans, (2) optimizing the allocation of available water resources to areas of demand, (3) optimizing certain physical dimensions of the system, and (4) optimizing the schedule of development of elements (reservoirs, canals, and pumping stations) which must be parts of the system. In specific terms of the research investigation reported herein, these capabilities were to be provided by development of:

- a transfer model for the optimal allocation of water to meet specified demands to the year 2020 at minimum total costs within the prescribed legal, financial, contractual, and political constraints,
- an optimal means of sizing, sequencing, and timing of project elements, and
- simulation models for the system.

The Problem

General Description

It is important that the reader recognize at the outset that the ultimate configuration of the Trans-Texas Division of the Texas Water System has been preliminarily fixed by initial planning studies. The numbers and locations of reservoirs, the lengths and routes of canals, and the pumping lifts required are all predetermined. Thus, the planning problem to be treated here has been reduced somewhat, although it remains formidable in many other dimensions. It remains for the planner to determine the sizes of all elements which will comprise the basic system and when these elements should be placed in service in order that the costs of construction, operation, and maintenance will be minimized over the planning period.

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[3] An application to the office of Water Resources Research for grant of funds pursuant to Title II of the Water Resources Research Act of 1964 as amended, for study of "Systems Simulation of Interconnected Multiple River Basins and Ground Water Aquifers for Planning, Design, and Management of a Total Water Resource," submitted by the Texas Water Development Board November 1967.

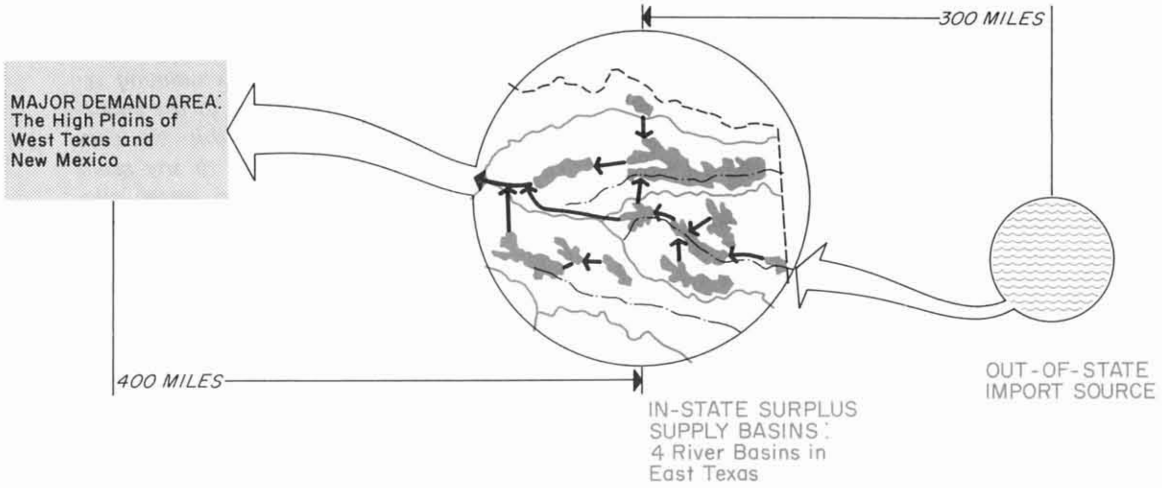

FIGURE 3.–MAJOR SUPPLY AND DEMAND AREAS FOR THE TRANS-TEXAS DIVISION OF THE TEXAS WATER SYSTEM

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

The system has the following unique characteristics which further complicates the planning problem:

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

Legal, political, and physical considerations all suggest a planning period of about 50 years. Over such a span of time it is anticipated that demands will rise steadily, even dramatically in some areas. As illustrated in Figure 4, a portion of the total demand, reaching a level in excess of 10 million acre-feet annually by 2020, must be met by supplemental supplies. Unfortunately, in-state supplies are not adequate, even if developed fully within the four eastern basins of the Trans-Texas Division, to meet total system demand after about 1985. Moreover, ground water supplies will be diminishing gradually over the period of early development of the imported water facilities, thus intensifying the need for importation.

Given the ultimate configuration of the proposed system and its characteristics as outlined above, as well as its initial condition at the outset of the 50-year period, the planner must find that plan which minimizes total costs of development. This entails three basic steps:

- determining a staging (sequencing) program for the addition of reservoirs and canals needed to meet the predetermined pattern of water demand,
- determining the size of each additional element, and
- determining an operating plan for the system as it is to be developed over the planning period.

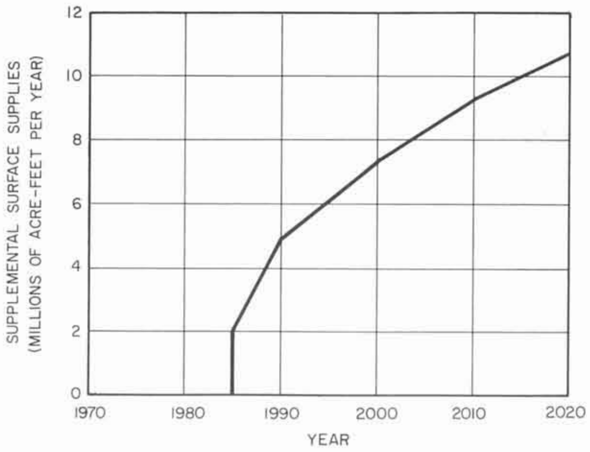

FIGURE 4.–SUPPLEMENTAL SURFACE WATER SUPPLIES REQUIRED FOR DELIVERY IN WEST TEXAS' INCLUDING DELIVERIES TO NEW MEXICO

Although these planning steps are dependent upon one another, a definite hierarchy exists in the order in which they are normally considered by the planner. First, decisions must be made concerning the ultimate sizes of system elements. Second, the timing for construction of each element must be determined, and finally, operating rules for the system must be fixed. All of these decisions, of course, are conditioned by the objective of minimizing total costs.

The problems identified in this planning sequence are actually interrelated and cannot be resolved independently. For example, there are definite tradeoffs between the capital costs of canals and reservoirs and the operating costs of transferring water. If a reservoir is constructed too small or too late, or both, system operating costs may be forced upward by the need to meet demands by supplying water from a remote reservoir or through a canal with a higher pumping cost. As a consequence of this interdependence, the whole assemblage of discrete problems must be considered at one time.

Since this investigation considered only the Trans-Texas Division of the proposed Texas Water System, there were certain constraints imposed which were unique to the system. Also, it was necessary to limit the scope of the research effort to that consistent with the time and financial resources available. Consequently, the following conditions were imposed on the general problem:

- All demands for and inputs of water are to be prespecified.
- Water quality is not to be considered.
- Conjunctive use of ground and surface water is not to be considered.
- All demands for water must be met.
- A 50-year planning period must be accommodated.
- Elements can be added to the system only at yearly intervals.
- Incremental staging of individual canal and reservoir sizes is not to be considered.
- Monthly time increments are to be used in simulating the system and allocating water from it.
- A minimum-cost objective function is to be used.

Despite these restrictions on the dimensions of the problem to be solved, it remains formidable. For a planning period of 50 years and a Trans-Texas system of 18 reservoirs[4], 30 canals, and 12 river reaches, it is necessary to determine 10,800 storage levels, 25,200 canal and river flows, 18 reservoir capacities, 30 canal sizes, and 48 construction times.

Mathematical Description

Mathematically, the equations to be solved are of the simplest algebraic type, merely statements of the law of conservation of mass. The basic equation, known in hydraulics as the Equation of Continuity and in hydrology as the Storage Equation, may be stated as:

$$\frac{\Delta \text{ Storage}}{\Delta t} = \Sigma \text{ Inflows} - \Sigma \text{ Outflows}$$

The several terms of the equation as it applies to a typical storage element (reservoir) in the Trans-Texas system are illustrated schematically in Figure 5 and are represented algebraically by the following statement:

$$\begin{array}{l}\text{The Rate}\\ \text{Of Change}\\ \text{In Storage}\end{array} = \left[\begin{array}{c}\text{Upstream}\\ \text{Releases}\end{array} + \begin{array}{c}\text{Pumped}\\ \text{Inflows}\end{array} + \begin{array}{c}\text{Unregulated}\\ \text{Inflows}\end{array} + \begin{array}{c}\text{Imports}\\ \text{(If any)}\end{array}\right]$$
$$- \left[\begin{array}{c}\text{Controlled}\\ \text{Releases}\end{array} + \begin{array}{c}\text{Pumped}\\ \text{Outflows}\end{array} + \begin{array}{c}\text{Local}\\ \text{Demands}\end{array} + \begin{array}{c}\text{Evaporation}\\ \text{Losses}\end{array}\right]$$

A complete set of continuity equations must be written for each discrete time step during which flows are considered as steady, i.e., the rate of change of

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[4] A modified system, comprised of 18 rather than the 22 reservoirs planned for the Trans-Texas Division, was used as a case for study in this research.

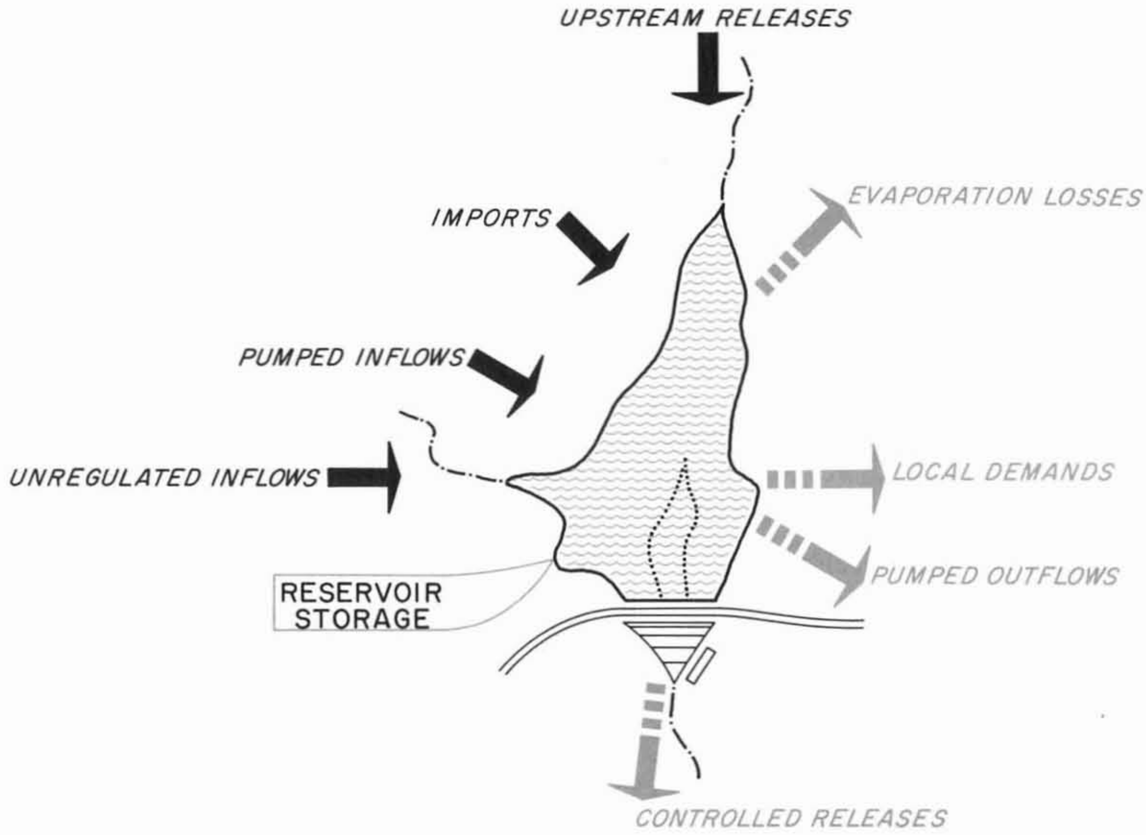

FIGURE 5.–TERMS IN THE CONTINUITY EQUATION FOR A TYPICAL RESERVOIR

storage is considered as constant. The set must include an equation for each reservoir and each canal or river junction, even though in the later case no net change in storage can occur. These equations must be solved for the system over the entire planning period to find canal and river flows, reservoir storage changes, and imported water required to meet demands, i.e., to satisfy continuity.

It is apparent from the dimensions of the problem that many more unknowns (canal flows, inputs, and reservoir levels) than equations can be identified. Thus, theoretically an infinite number of solutions is possible. However, since a minimum-cost solution is desired, the problem can be constrained in such a way as to result in a unique solution, that configuration, schedule, and operating plan which corresponds to the least cost. Conventional analytical solution techniques are not satisfactory for this task and optimization procedures, such as those utilized in operations research, must be involved.

An Approach

Four Phases

While it is theoretically possible to employ a single optimization technique to solve the problem, a cursory review of the number of variables, restraints, and other special conditions indicated that a practical solution probably could not be found by formal procedures within the reasonable bounds of time, money, and computer capability available. As a result it was decided to develop a screening technique which would have the capability to reduce drastically, in a series of steps, the numbers of alternatives to be considered. This technique, which utilizes a variety of optimization routines to find "near optimum" solutions at much lower computation cost and effort than any single procedure, was a major product of the research effort reported here.

The essence of the approach for optimizing the Trans-Texas Division of the Texas Water System is embodied in four major phases:

I. Initial Element Sizing and Reservoir Operating Rules

II. Initial Screening of Development Plans

III. Secondary Screening of Development Plans

IV. Final Screening of Development Plans

Although this approach does not guarantee a minimum-cost solution, it does permit the planner to inject his judgment and experience into the screening process to approach the minimum-cost solution as closely as he desires. This enables him to eliminate illogical results and provides him with an opportunity to integrate into the decision making process those considerations that cannot otherwise be expressed in quantitative terms.

Four Computer Programs

To provide this capability to the planner four computer programs were necessary and had to be developed. They are designated as:

- Stage Development Program
- Simulation Program I (SIM-I)
- Simulation Program II (SIM-II)
- Allocation Program

These programs are briefly described below and are discussed in detail in Chapters IV, V, and VI.

The *Stage Development Program* is an optimization procedure designed to estimate the best plan for sequencing the addition (placing in service) of project elements. It requires, as a subroutine, one of the simulation programs or the allocation program.

The simulation and allocation programs constitute a hierarchy of successively more complex, yet more *realistic* procedures for simulating and evaluating alternative development palns. *Simulation Program I,* or simply SIM-I, provides the planner with a rather crude but rapid and efficient simulation procedure. Certain simplifying assumptions are made in this program concerning the system's configuration and the rules by which it must operate. These assumptions are such as to reduce the problem to one that can be solved directly from an explicit set of algebraic equations.

Simulation Program II, or SIM-II, represents the next higher level of sophistication in representation of the real system. Some of the constraining assumptions of SIM-I are relaxed in SIM-II, particularly as concerns system configuration. More flexibility is built into the program and an optimizing scheme is utilized.

The *Allocation Program* gives the planner a formal means of solving for the "optimum." It is constructed around the so-called Out-of-Kilter Algorithm and is a highly flexible means for characterizing optimal system behavior under conditions most nearly approximating those of the prototype.

Use of Programs in Planning

The four-phase system planning process outlined above requires the utilization of each of the four special programs in a way which leads logically toward selection of a minimum-cost solution acceptable to the planner. A certain amount of experience with the prototype, and the real data which characterize it, is essential to most effectively use the programs, but the procedure is structured so that the planner can make value judgements when and where they are appropriate. In general, the programs correspond to each major planning phase as illustrated in Table 2. Some additional details of program applications and limitations are summarized below.

Table 2.—Four Phases of the Evaluation and Selection Process, and the Corresponding Computer Programs

	PHASE	PROGRAM
I.	Initial Element Sizing and Reservoir Operating Rules	Allocation Program
II.	Initial Screening of Development Plans	Stage Development Program and SIM-I
III.	Secondary Screening of Development Plans	SIM-II
IV.	Final Screening of Development Plans	Allocation Program

Phase I: Initial Element Sizing and Operating Rules

The first step in the system planning sequence is to estimate tentatively the sizes of reservoirs and canals and to determine approximately a reasonable set of operating rules for the reservoirs. This is accomplished in two separate applications of the Allocation Program. In the first application, sizes of system elements are determined, corresponding to a fully developed minimum-cost system operating with average streamflows and meeting maximum demands. In the second application, operating rules are derived for the system with reservoirs and canals as preliminarily sized, but for conditions of average streamflows and average demands. The rules, thus derived, provide descriptions of storage changes in individual reservoirs as functions of the fraction-full of aggregate storage capacity of the system.

Maximum demands for the Trans-Texas Division, used to estimate sizes of system elements, are estimated to occur at the end of the planning period, in the year 2020. Average demands, upon which tentative operating rules are based, are calculated as the arithmetic means of yearly demands over the 50-year period. Average streamflows, used in both applications of the Allocation Program in this phase of the planning sequence, are the arithmetic means of historical observations.

The two simulation programs, SIM-I and SIM-II, employ the products of this planning step. SIM-I uses the derived operating rules and the preliminary reservoir sizes; SIM-II uses both of these as well as the preliminary canal sizes.

Phase II: Initial Screening

The objective of this phase of planning is to eliminate clearly inferior sequences of reservoir and canal construction times and to improve the better sequences to the point that no further significant cost reduction can be achieved.

As a first step in this phase an initial sampling is made of the enormous, but finite, number of possible sequences. The sample is chosen large enough so that the probability of obtaining a solution near the global optimum[5] is reasonably high. This sample, perhaps a hundred or so, is initially screened with SIM-I on the basis of a cost criterion.

SIM-I, because of its economy of operation, is an ideal tool for this initial screening. It derives this advantage in part by a simplification in the system configuration from a general structure containing loops to one which is "tree-shaped." This modification, illustrated in the simple example of Figure 6, insures that the resulting set of continuity equations can be solved simultaneously to obtain a unique solution. It should be noted, however, that several tree-shaped structures are possible from the same general configuration; thus the planner must exercise some judgment in selecting the shapes to study.

The Stage Development Program employs an optimization technique called *response surface exploration.* A response surface is comprised of the loci of system costs, including penalties for deficits that may occur, plotted as dependent on the times when elements of the system are placed in service. A simple example will serve to illustrate the general procedure.

If there are only two system elements—a canal and a reservoir—the surface may be considered as three dimensional, perhaps of the shape depicted by the cost contours shown in Figure 7. For a planning period of 25 years there are $25^2 = 625$ possible combinations of start times for the two elements and thus 625 independent cost determinations. Certain combinations of start times may prove on inspection to be incompatible, between the two elements, thus blocking out some parts of the response surface, a priori. The remainder of the surface must then be "explored," or sampled, in an effort to find those "pits" which correspond to minimum-cost solutions. False minima are possible, as illustrated in Figure 7, and there is no absolute guarantee without examining *all* values that a global minimum will be obtained. The practical objective of the search exercise is to find a minumum which has some specific probability of being within a reasonable predetermined range of the global optimum solution. It can be easily seen, from this simple example, that even for a system of modest dimensions the number of alternatives can be staggering. The Stage Development Program has been designed specifically to focus the search on a good initial plan (or plans) and then to improve on it by systematically modifying the staging sequence to the point where no further reductions in the present worth of the project cost can be achieved. At this point the planner will have identified a low-cost plan to which may be attached certain probability statements concerning its relation to the least costly alternative.

Phase III: Secondary Screening

Alternative development plans which survive initial screening, perhaps less than 5 percent or so of the original sampling of the response surface, are reexamined more closely with SIM-II. In this secondary screening the planner can review the sensitivity of cost to changes in element sizes and operating rules, seeking to further reduce overall costs.

SIM-II relaxes two restrictions imposed by the use of SIM-I: the need to use a tree-shaped structure and the requirement that flow may be in either direction. In this more advanced simulation technique loops in the system are permitted to exist and the direction of flows in either canals or river reaches may be constrained to conform with reality. The reader will recall, in this connection, that these modifications result in an increase in the number of unknowns well beyond the number of equations which can be formulated. It follows, then, that SIM-II must use a technique which finds, from an infinite number of possibilities, that solution which is optimal. For this purpose the Out-of-Kilter Algorithm, which constitutes the core of the Allocation Program, was also incorporated into SIM-II.

This added degree of sophistication in the screening process is gained at some significant cost, as the running time on the computer of SIM-II is about two orders of magnitude greater than that of the much simpler SIM-I. Consequently, the planner would normally be inclined in this phase to submit only those

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[5] The true optimum among all of the possible sequences.

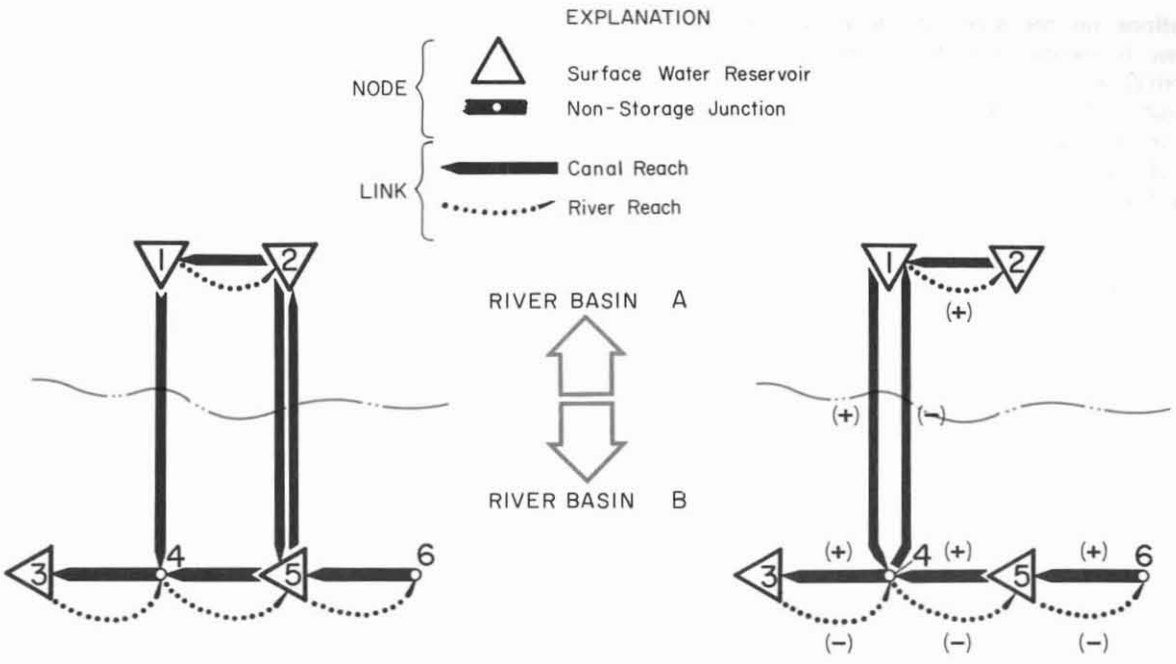


FIGURE 6.–COMPARISON OF GENERAL (LEFT) AND TREE-SHAPED STRUCTURES

alternatives for study which are attractive possibilities to emerge as the least costly among all those which entered Phase II. It may be feasible, as improvements are made in SIM-II, either to use it in evaluation of all alternatives which have passed the final step in the initial screening or to incorporate it directly into the Stage Development Program.

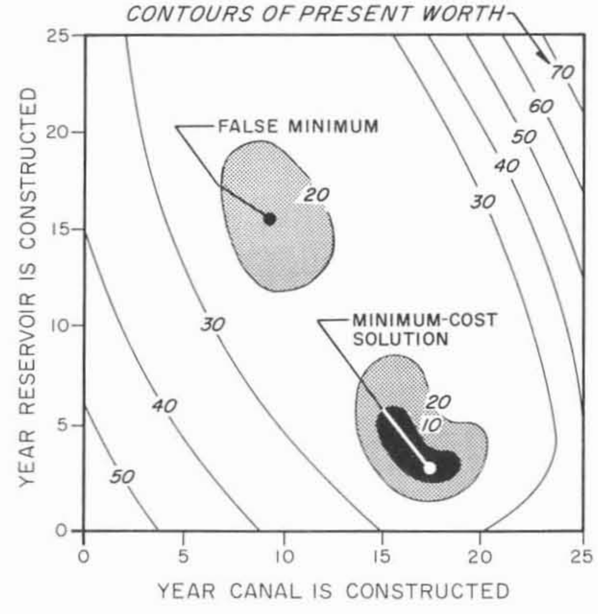


FIGURE 7.–EXAMPLE RESPONSE SURFACE FOR TWO-ELEMENT STAGING PROBLEM

Phase IV: Final Screening

Final screening is accomplished with the Allocation Program, the most comprehensive of all those employed in the planning process. Because of its higher operating cost, occasioned by the formal optimizing technique utilized, this program would normally be used to study only a limited number of truly superior candidates and to single out that unique plan which deserves to be designated as "best."

Comprehensiveness is obtained in the Allocation Program by relaxing all assumptions regarding system configuration, canal flows, and operating rules. However, certain approximations concerning evaporation losses and pumping lifts are made, which distinguish this program from SIM-I and SIM-II.

The Allocation Program, like SIM-II, uses the Out-of-Kilter Algorithm to evaluate alternatives. However, in this phase of planning, reservoir storage changes are computed rather than predicted by the preliminary operating rules derived in Phase I. This results in expanding the scope of the problem and requires a substantially increased computational effort over that of SIM-II.

The primary product of the Allocation Program is a minimum cost of transferring water to demand points over the entire planning period through the stipulated system of reservoirs, canals, and rivers. Related products of the program are the "marginal" or incremental operating costs that are incurred by placing specific limitations on the sizes of canals and reservoirs, as opposed to leaving the problem unrestrained in the hope of finding an even less costly solution. Through a series of trials with the program the planner may, by the exercise of judgment tempered by experience, find that desirable combination of sizes which is both practical and of lowest cost.

The concept of an organized stepwise approach to the planning of large, multicomponent systems is not new with this investigation. What is new is the incorporation into the planning process of specific computational capability to screen, simulate, and optimize alternative water development programs. The balance of this report is concerned with amplifying the methodology proposed and providing in-depth descriptions of the programs, the algorithms and the data required, and the specific capabilities, assumptions, and limitations pertinent to each of these.

IV. STAGE DEVELOPMENT PROGRAM

Purpose

The purpose of the Stage Development Program is to estimate the minimum-cost sequence or sequences of dates when reservoirs and canals are needed during a planning period to satisfy all demands for water. This program eliminates all poor and illogical sequences and improves the best ones until no further cost reductions can be made. It uses SIM-I, the crudest of the simulation programs, to evaluate such alternatives. Consequently, those sequences which are tentatively judged "best" in the evaluation must be reevaluated using the more refined and realistic programs, SIM-II and the Allocation Program.

Concepts

The Stage Development Program focuses initially on obtaining a good initial set of alternatives for system development, i.e., sequences of dates for placing system elements (reservoirs and canals) in service to meet stipulated demands. This initial step of Phase II planning is accomplished in either of two ways: (1) by performing a preliminary balance of net surface water supplies (excess of supply over demand for an historical period), or (2) by random sampling of the myriad alternative sequences. Once a good set of alternatives is identified, the Stage Development Program proceeds through an organized search procedure either to eliminate those choices identified in the initial step which are clearly infeasible or inferior, or to improve on those which rank "high" in calculated response, i.e., those which are lowest in cost.

SIM-I is used to evaluate all alternatives submitted to the Stage Development Program, providing two measures of system response: *total present worth* of the capital, operation and maintenance, and importation costs of the plan; and the plan's *total cumulative deficit* of supply versus water demand. Present worth in SIM-I is determined by applying a fixed discount rate to all costs that are incurred during the planning period—including operation and maintenance expenses, costs of imported water, and the capital expenditure for each project element—and bringing these costs forward so that they represent the required dollar investment at an appropriate current date. The cumulative deficit represents those demands that could not be satisfied over the development horizon if the reservoirs and canals are placed in service according to the stipulated schedule.

These two measures of system response were transformed into a single dependent variable, called the *created response,* by arbitrarily imposing a penalty, an added cost, on those alternatives in which deficits can be anticipated. The created response is defined as the present worth of the plan's cost, multiplied by a penalty function. Algebraically, it is given by the relation

$$CR = C \times P(D)$$

where

$$C = \text{present worth cost}$$

$$P(D) = \begin{cases} 1 + \left(\frac{D}{2000}\right)^2 & ; \text{ if } D > 0 \\ 1 & ; \text{ if } D \leq 0 \end{cases}$$

in which D is the cumulative deficit of all reservoirs over the planning period expressed in thousands of acre-feet.

The form of the penalty function, depicted graphically in Figure 8, was selected with the specific objective of forcing the search for superior plans into the low-cost regions of the response surface. It does not represent the real economic penalties that might occur in a deficit situation. The implicit assumption is made in choosing this relationship that plans which allow deficits to occur are not viable alternatives for future consideration in the planning process. That this may actually not be the case is acknowledged. It is possible to modify this characteristic of the Stage Development Program in the future, should it prove necessary.

The Stage Development Program, which is summarized in Table 3, consists of a set of three subroutines, each one providing information about the sequencing and timing of the addition of canals and reservoirs over a given planning period. These three subroutines are concerned with: (1) a net surface water balance which relates storage needs to time, (2) a random sampling of dates for adding reservoirs and canals, with the costs of each "sample" (alternative schedule) estimated by SIM-I, and (3) a deterministic, sequential search, also implemented using SIM-I, which attempts to improve a given set of dates. The respective subroutines which implement these computations are named VOLSTG for volume staging, EXPLOR for random sampling, and MSP for Method of Successive Perturbations. The characteristics and mode of application of each of these subroutines are described briefly on the following page.

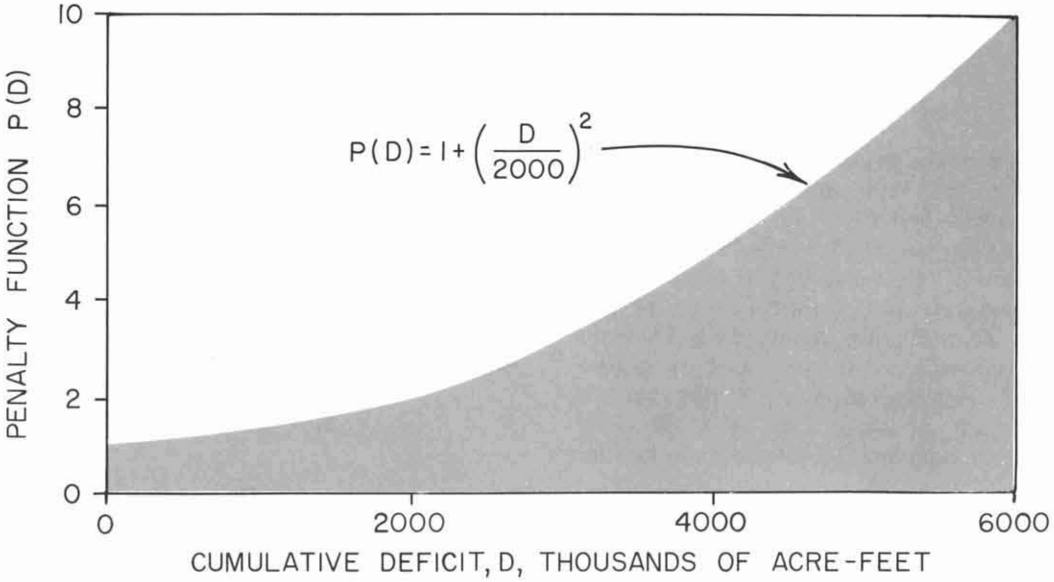


FIGURE 8.—PENALTY FUNCTION USED TO REDUCE THE CUMULATIVE DEMAND DEFICIT

Table 3.—Summary of the Subroutines in the Stage Development Program, Their Purpose, and the Methodology Used

SUBROUTINE	PURPOSE	METHODOLOGY
VOLSTG	To provide a good estimate of the time-staged storage requirements	Assumes an infinite storage capacity and conducts a mass balance over time
EXPLOR	To locate attractive starting points for the sequential search (MSP)	Randomly picks plans and evaluates their performance over the planning period using SIM-I
MSP	To improve the plans obtained fromEXPLOR	Uses a discrete integer pattern search procedure, the Method of Successive Perturbations, in combinations with SIM-I

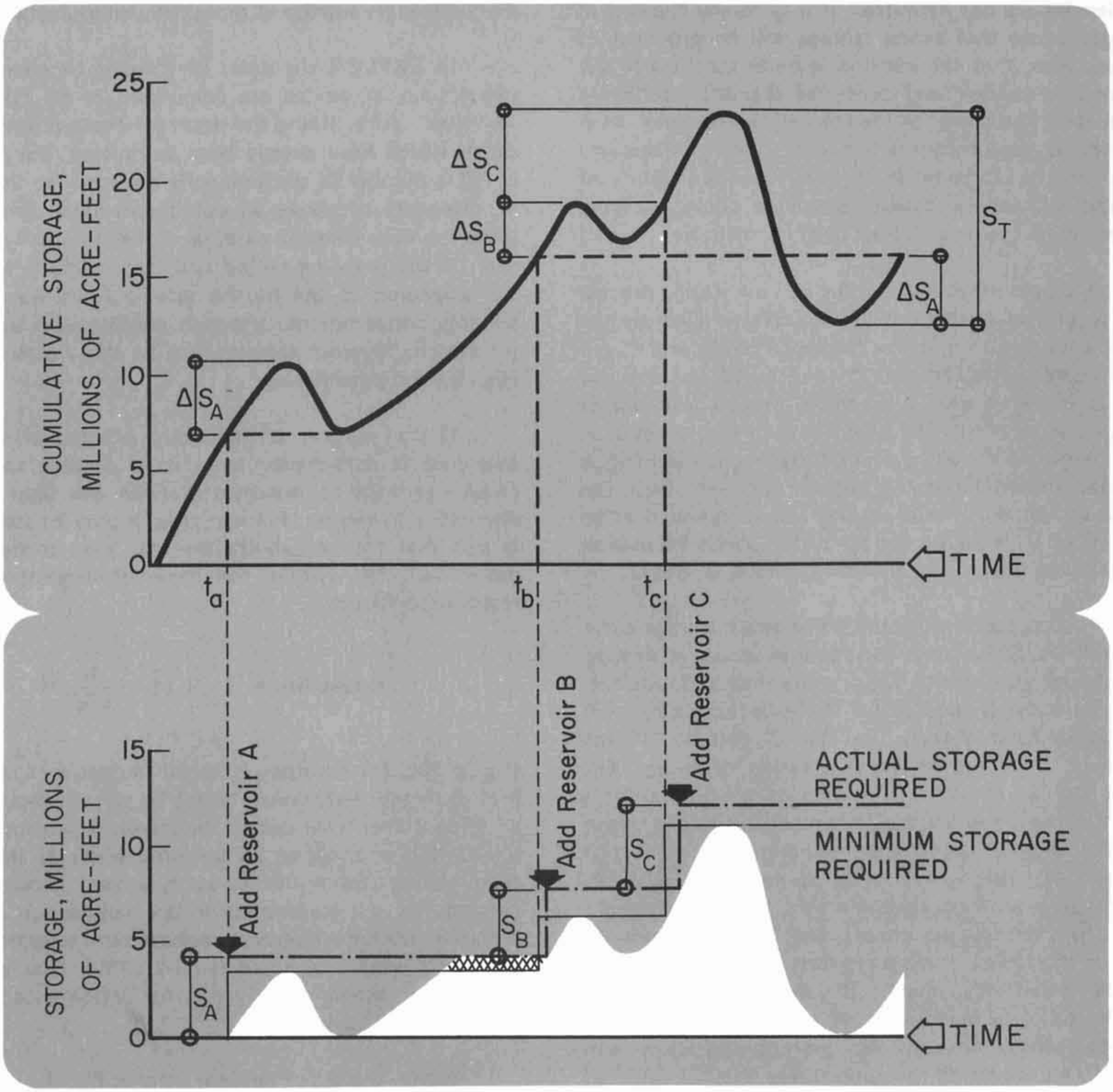
Subroutine VOLSTG

The purpose of the volume staging analysis is to estimate the minimum storage requirements over time, to obtain a sequence or sequences of dates that reservoirs should be added to the system, and to indicate the length of time the need for imported water can be deferred. VOLSTG can be used as an alternate to subroutine EXPLOR as the first step in Phase II of the planning process.

In applying this subroutine, runoff and demands over the entire planning period must be known. To estimate storage requirements, VOLSTG first defines a cumulative storage curve by aggregating all inflows, satisfying all water demands, and estimating evaporation losses while operating under the assumption that the system has an infinite capacity to retain surplus waters. For the purpose of illustrating the volume staging analysis technique, consider the unconstrained cumulative storage curve shown in Figure 9a.

To estimate minimum storage requirements from such a curve VOLSTG first identifies all peaks and troughs on the curve. Then, moving forward in time and considering each successive trough, it takes a backward look from each trough and finds the differences between it and all preceding peaks. The maximum difference is the minimum storage required to survive the drawdown period that terminated in the trough being investigated. If this requirement is less than one previously found, the preceding storage requirement is adequate. However, if the requirement is greater than any previously found, the system needs an increase in storage. A third possibility exists, that the new storage requirement could be greater than the available storage. When this occurs, water must be imported if all demands for water are to be satisfied.

To find the dates when storage increases are required, VOLSTG evaluates successively each trough for which a storage increase has been determined. It locates the first point on the unconstrained storage curve with a value equal to that of the trough plus an amount equal to the previous maximum storage requirements. The date corresponding to this point is the latest time the entire storage increment, ΔS, can be added and still be effective in surviving the drawdown period. If there exists more than one peak between this date and the date corresponding to the trough, the storage increment



a. UNCONSTRAINED STORAGE

b. CONSTRAINED STORAGE

FIGURE 9.–GRAPHICAL REPRESENTATION OF THE VOLUME STAGING ANALYSIS

can be added in smaller segments, where each segment is just large enough to conserve the flow that produced the peak.

Figure 9a illustrates graphically how this technique would be employed to find the storage requirements for the expected curve depicted. Figure 9b shows the minimum expected storage requirement and the storage levels that would result if the predicted schedule for meeting minimum storage requirements could actually be implemented.

However, at this stage in the planning sequence a critical question, as yet unanswered, is:

> *When should specific storage capacity, feasible of development, actually be placed in service?*

VOLSTG seeks to answer this question, assuming that the sizes of reservoirs and the sequence in which they will become available for service are already known. It simply adds the known capacities of reservoirs to the existing storage in the system and tests to determine whether or not storage needs are satisfied. Since deficiencies are not permitted, it is generally the case in this procedure that excess storage will be provided. It follows, also, that the method is quite sensitive to the assumed hydrologic and predicted demand conditions which form the bases for the volume staging curve. As it now stands, the procedure is basically deterministic and no statements can be made concerning the probability of a particular volume staging sequence being within a predetermined range of a least costly alternative.

A simple illustration of the volume staging process as it would be carried out by VOLSTG is given by the example of Figure 9. Three reservoirs, A, B, and C, are to be constructed according to a fixed sequence to provide increments of 4, 3, and 4 million acre-feet of storage, respectively. The problem is to find when each must be placed in service so that maximum assurance is provided that the demand will be satisfied. Over the period shown the maximum demand is indicated to be satisfied by a minimum storage of S_T, about 1.5 million acre-feet less than the total of reservoirs A, B, and C.

In accordance with the constrained storage curve of Figure 9b, Reservoir A must go into service at time t_a, even though its capacity, S_A, is more than that required, ΔS_A. Reservoir B, because of the excess capacity of A can be delayed slightly, as can C because of the accumulated reserve of the two earlier reservoirs. The actual storage provided, in stages at t_a, t_b, and t_c, is shown in the figure by the dashed curve, situated in this example slightly above the minimum required. It is possible, of course, because of restraints on available capacity at feasible construction sites, that deficits might result for certain sequences. The method tends to allocate storage as early as needed and to accumulate deficits toward the end of the planning period. The planner may intervene in this procedure to try sequences or times which he considers more practical or economical. He is offered the opportunity through SIM-I of testing for hydraulic performance and cost. Subsequently he may wish to submit the better sequences to the Method of Successive Perturbations in an attempt to reduce costs toward a minimum.

Subroutine EXPLOR

EXPLOR provides the planner with a means for selecting, by a random process, the dates when reservoirs and canals might be added to the system. It is assumed in application of EXPLOR that sequences have not been completely predetermined, as in the case of VOLSTG, but the planner has the liberty of fixing the dates for certain elements to be placed in service. All possible combinations generated in the process can be considered, although the method will produce sequences which for one reason or another may be clearly infeasible. These may usually be discarded by inspection, but a simulation check with SIM-I may be used to provide additional guidance as to whether certain alternatives are worthy of more detailed evaluation.

In EXPLOR the dates for placing an element of the system in service are considered to be "decision variables." After fixing the dates for those reservoirs or canals which have already been authorized, the planner is left a number of decision variables equal to the total of reservoirs or canals as yet unscheduled. Since the times for each element must lie within the first and last year of the planning period and, for practical reasons, are scheduled to the nearest year, a finite number of possible combinations, although enormous, is available for search. Random samples may be easily drawn from among these possibilities.

If the number of randomly selected alternative schedules is sufficiently large it is possible to make certain probability statements about the least costly alternative in the set. For example, it may be stated for N sets that the probability that the least costly alternative will fall within the lower P percent of the response surface is:

$$\text{Probability} = 1 - (1 - \frac{P}{100})^N$$

If N is 100, for example, it would be possible to declare that the least costly would have a 99 percent probability of being drawn from within the lowest 5 percent of the set. If N is as small as 30 the probability of the least costly being within the lowest 5 percent is only 88.7 percent. In our experience in the application of the program 100 sets of alternatives have been selected, each of which would be simulated by SIM-I. The created response, including penalty cost for deficiencies, would be determined for each set.

Within the set of random samples the one with the lowest created response is usually judged "best." It should be noted that this is not necessarily the least costly of all the sets if penalties for deficiency are omitted, hence some judgment on the part of the planner is required in selecting those sets which are subjected to the Method of Successive Perturbations.

Subroutine MSP

The objective of the Method of Successive Perturbations is to find a low point on the response surface, hopefully one which corresponds to the least costly sequence for placing reservoirs and canals in service. Because the surface is not necessarily concave in all parts of the region sampled there exists the possibility of more than a single depression. Thus, there is no absolute guarantee that a search beginning at a low point and proceeding toward the bottom of the depression will actually terminate at the absolute minimum. It may be necessary to apply MSP to several low starting points in order to improve the chance of finding the least costly alternative.

Starting points for the search are the lowest-cost sequences produced by either VOLSTG or EXPLOR. These sequences are changed slightly, or perturbed, in an organized way by MSP to determine whether or not the costs can be lowered. Since the decision variables are integers, perturbations are also integers, +1 year or -1 year. The procedure is rather straightforward, although highly organized. It can best be explained by means of a simple example.

Figure 10 illustrates a complete perturbation step for a system of three elements with 10 possible starting times for each. The initial sequence is given, presumably a low-cost sequence from VOLSTG or EXPLOR. Subroutine MSP begins with element A, determining the costs corresponding to starting A a year earlier or a year later. It then compares these costs, corresponding to perturbed sequences, to the original cost and adopts the sequence which gives the lesser cost. This procedure is applied successively to the elements next in order, each time retaining the perturbed sequence corresponding to the lowest created response. One pass through the system, in this case one comprised of three elements, constitutes a perturbation step. As many steps can be taken as needed to find the best sequence, using reduction in created response as a criterion for deciding when to terminate the process. For very large systems a large number of simulations may be required, hence the planner would most likely choose to utilize SIM-I, already incorporated with MSP as a part of the Stage Development Program.

It was discovered, during development of the technique, that a substantial reduction in computational effort could be realized by retaining the pattern of the antecedent perturbation step and using this to guide the course of successive steps. For example, the result of the first step illustrated in Figure 10 was not to change the date for A, to start B a year earlier, and C a year later. This pattern, 0, + 1, - 1, suggests that in the next step further reductions in created response might result if B were moved up and C retarded, while A is left unchanged. In the perturbation step illustrated in Figure 11 this suggestion is followed with the result that B moves forward two more years and C is moved back two more years. Using this procedure, the number of perturbations is reduced by eliminating many of those which are not likely to improve the result.

The reader will note that the sequence of the perturbation operation is discretionary with the planner and will also affect the result. It would appear logical that those elements closest to points of demand and, hence, most likely to provide low-cost local supplies, should be built first. Accordingly, the planner might elect to have these considered first in the perturbation sequence, placing the more costly elements far from demand areas lower in rank. Here again, it is necessary that experience and judgment figure prominently in the planning process.

Special Input Requirements

Hydrologic and demand data, as well as data on costs, required for the Stage Development Program are supplied from a standard input tape, described in detail in Chapter VII. Special input requirements for the program concern primarily the sizes of elements, sequencing, and certain dimensions of the problem to be solved. For VOLSTG a list of reservoirs and reservoir sizes is required and the sequence of their addition to the system must be stipulated. For EXPLOR and MSP a list, referencing decision variables to reservoirs and canals, is needed. The number of random samples to be drawn for EXPLOR and the maximum number of perturbation steps in MSP must also be given.

The special information required for SIM-I, which is at the core of the Stage Development Program, is described in the succeeding chapter on simulation programs.

Capabilities

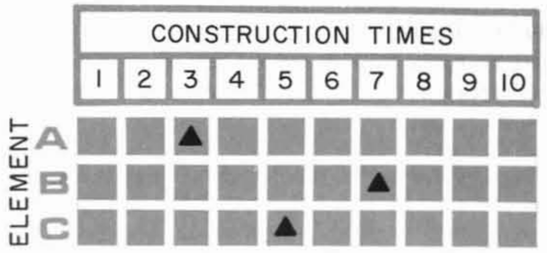
The Stage Development Program provides the planner with a set of tools which will facilitate his selection of attractive alternative schedules for implementation of a system to meet a fixed pattern of demands over space and time. It operates directly on given hydrologic data and presumes a knowledge of the configuration of the proposed system and the demands it must serve.

Exploration of the response surface for low-cost alternatives is initiated by either VOLSTG or EXPLOR to identify possible sequences for placing system elements in service. These two subroutines invoke a few simple rules to direct the search toward choices which have the greatest prospect of lying near a minimum-cost sequence. The planner participates in this process, injecting his judgment to eliminate unreasonable choices and to reduce the search effort. Many of the decisions are made objectively in the program logic, but the planner has an overriding capability to direct the process.

Using the Method of Successive Perturbations, the planner is afforded an organized technique for converging on superior sequences, those which are lowest in created response. He is not guaranteed an absolute minimum, but is allowed in this technique to make some probability statements concerning how his better choices relate to the minimum. In general, his prospects for

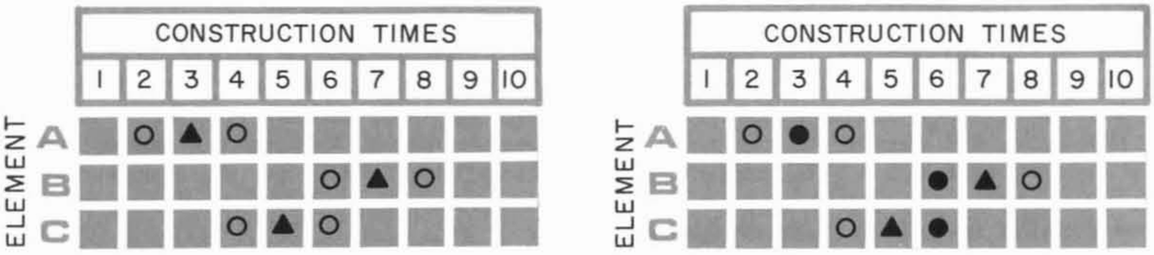
EXPLANATION:

- ▲ Original Time
- ○ Perturbed Time
- ● Best Time After Perturbation



ELEMENT	1	2	3	4	5	6	7	8	9	10
A			▲							
B							▲			
C					▲					

a. INITIAL CONSTRUCTION TIMES



ELEMENT	1	2	3	4	5	6	7	8	9	10
A		○	▲	○						
B						○	▲	○		
C				○	▲	○				

b. SUCCESSIVELY EVALUATE ±1 YEAR PERTURBATIONS IN THE CONSTRUCTION TIMES FOR EACH ELEMENT

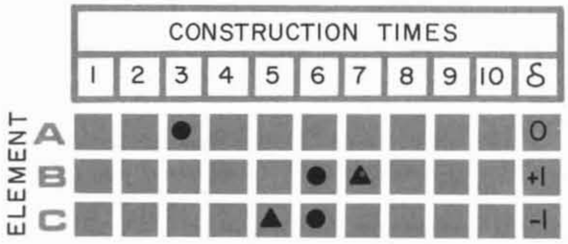
ELEMENT	1	2	3	4	5	6	7	8	9	10
A		○	●	○						
B						●	▲	○		
C				○	▲	●				

c. FOR ALL ELEMENTS RETAIN THE BEST OF THE THREE CHOICES: *THIS IS ONE PERTURBATION STEP*

FIGURE 10.–METHOD OF SUCCESSIVE PERTURBATIONS: ONE PERTURBATION STEP

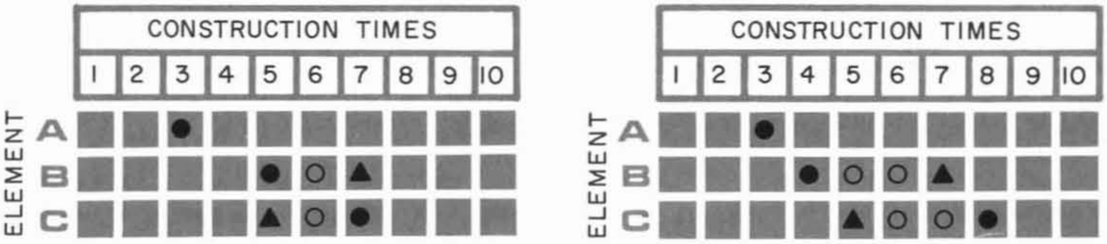
EXPLANATION:

- ▲ Original Time
- ○ Perturbed Time
- ● Best Time After Perturbation



ELEMENT	1	2	3	4	5	6	7	8	9	10	δ
A			●								0
B						●	▲				+1
C					▲	●					-1

a. COMPUTE PATTERN, δ, FROM PERTURBATION STEP



ELEMENT	1	2	3	4	5	6	7	8	9	10
A			●							
B					●	○	▲			
C					▲	○	●			

b. APPLY PATTERN TO RESULTS FROM THE PERTURBATION STEP

ELEMENT	1	2	3	4	5	6	7	8	9	10
A			●							
B				●	○	○	▲			
C					▲	○	○	●		

c. CONTINUE TO APPLY PATTERN UNTIL NO IMPROVEMENTS ARE MADE

FIGURE 11.–METHOD OF SUCCESSIVE PERTURBATIONS: ACCELERATION PATTERN

examination of truly attractive alternatives are greatly expanded while at the same time casting aside objectively the many possibilities which he might have examined fruitlessly.

The cost and effort in utilizing the Stage Development Program are closely related to the simulation of system performance and the estimation of cost. These functions are carried out by SIM-I, a low-cost but simple simulation routine which is used for each alternative examined in VOLSTG, EXPLOR, or MSP. The cost of using SIM-I is least with the volume staging technique, moderate with the random sampling procedure, and greatest with the Method of Successive Perturbations. Overall costs are proportional to:

- the size of the problem, i.e., the number of reservoirs and canals and the time period studied,
- the size of the random sample drawn in EXPLOR,
- the number of starting points considered in the MSP, and
- the topography of the response surface as revealed by the rate of convergence during use of the MSP.

The ultimate output of the Stage Development Program will be the dates when reservoirs and canals must be added to the system in order to meet the prescribed demand at lowest cost subject to the limitations of the techniques as described. Certain of these limitations, such as those concerned with operating rules, canal sizes, estimating evaporation losses, etc., will be removed by subsequent applications of SIM-II and the Allocation Program.

V. SIMULATION PROGRAMS

Purpose

The purposes of both SIM-I and SIM-II, the two simulation programs developed in the study, are to:

- *describe the hydraulic behavior of a water resource system for given hydrologic inputs and reservoir operating rules, and*
- *estimate the costs of construction, operation, and maintenance of a particular alternative over a planning period.*

While both programs have identical objectives from the planner's viewpoint, they differ in the degree of realism provided in representing the prototype system, in the accuracy of the answers obtained, and in the cost of executing a simulation.

These differences were provided intentionally; they resulted directly from a need to provide the planner with flexibility in choice between the quality of the information provided by a simulation and the cost of securing it. SIM-I is simple and inexpensive to operate; hence, it is useful at an early stage of planning when many alternatives must be considered but exactness of the resulting cost is not so critical. Later on, when the choices have been narrowed somewhat, SIM-II can be used; cost of simulation will be higher, but results will be more representative of the prototype. The tradeoff between cost of operation and degree of sophistication of the programs was an important concern throughout the programs of development reported herein.

Aside from these differences in usage, the programs have many common characteristics. The basic principles are the same for each, even though the details of structure are not. In this chapter the common properties of the programs are presented and discussed first. Subsequently, those characteristics which give SIM-I and SIM-II their uniqueness are described.

Program Similarities

General Formulation

Mass balances, over both space and time, form the fundamental set of equations that must be solved in both SIM-I and SIM-II. Figure 12 illustrates the basic terms that must be included in a mass balance equation for a typical reservoir.

Such an equation, formulated for the jth reservoir of a system and time period k, would be:

$$\sum_{i=1}^{m} A_{ji} Q_{ik} - \frac{(S_{j,k+1} - S_{jk})}{\Delta t} = D_{jk} + E_{jk} - U_{jk} - I_{jk}$$

$$j = 1,\ldots,n$$

$$k = 1,\ldots,L$$

where

$$A_{ji} = \begin{cases} +1 \text{ if flow in link i enters node j} \\ -1 \text{ if flow in link i leaves node j} \\ 0 \text{ if link i is not connected to node j} \end{cases}$$

Q_{ik} = Flow in link i during time period k (this can either be a pumped input/output or an upstream/downstream release)

$S_{j,k+1}$ = Storage contents of reservoir j at the end of time period k

S_{jk} = Storage contents of reservoir j at the start of time period k

Δt = Length of time period

D_{jk} = The local demand from reservoir j in time period k

E_{jk} = The evaporation loss from reservoir j during time period k

U_{jk} = The unregulated inflow into reservoir j in time period k

I_{jk} = Quantity imported directly into reservoir j during time period k (this can occur at only one node in the system)

L = Number of time periods

m = Number of links, either pump-canals or rivers

n = Number of nodes, either reservoirs or non-storage junctions.

A similar equation can be written for all reservoirs in the system and for each time period to be considered. The set of equations for n reservoirs and L time periods must then be solved to provide the desired description in space and time of the system's behavior.

Both of the simulation programs partition this set of equations into subsets for each period by using

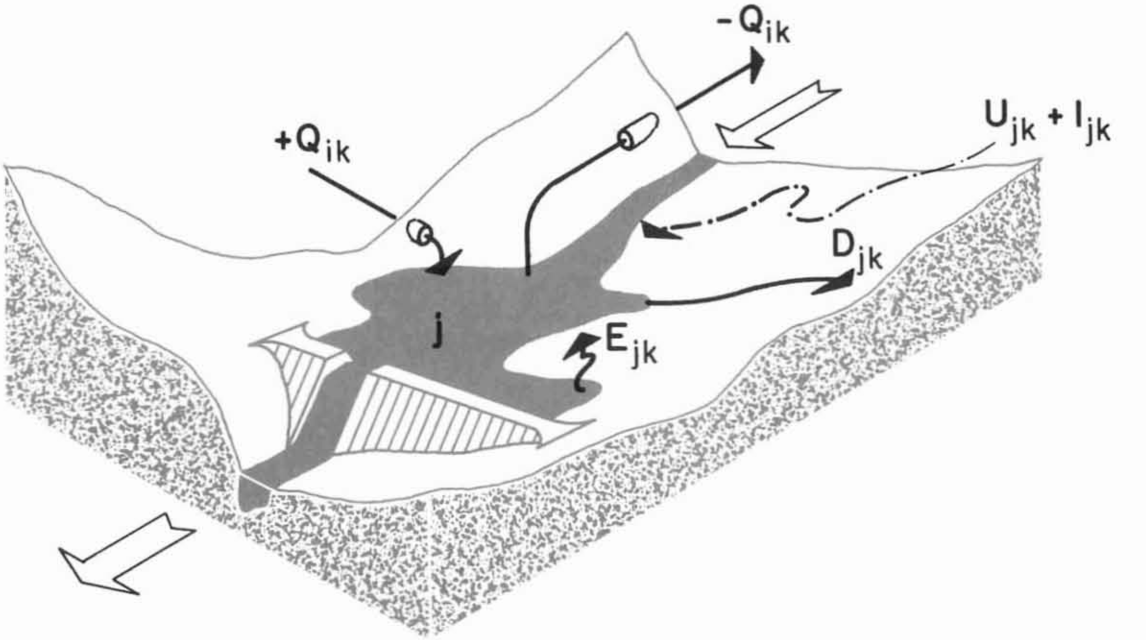


FIGURE 12.–BASIC TERMS IN A MASS BALANCE FOR A RESERVOIR

operating rules that specify reservoir storage contents. Application of these rules results in fixing the storage terms of the equations. Since it is presumed that local demand, unregulated inflow, evaporation, and imports are given, the only unknown terms remaining are the link flows, Q_{jk}. The resulting subset of equations for a time period, k, can then be written as:

$$\sum_{i=1}^{m} A_{ji} Q_{ik} = \frac{(S_{j,k+1} - S_{jk})}{\Delta t} + D_{jk} + E_{jk} - U_{jk} - I_{jk};$$

$$j = 1,\ldots,n$$

For a system with n nodes and m links, there are n continuity equations and m flow variables. In general, the number of flow variables tends to be greater than the number of equations. If this is the case, a direct simultaneous solution of the set of equations is not possible. There are at least two alternative courses through which it is possible to reach a solution to the problem thus posed; either

- reduce the number of flow variables (links) to the number of independent continuity equations (nodes) by making certain assumptions and then solve the resulting equation set directly, or
- retain all of the flow variables, define an objective function, and use an optimization technique to find the best of all possible solutions.

Both approaches were adopted, one for SIM-I and the other for SIM-II.

SIM-I contains enough assumptions to reduce the number of unknown link flows to the number of independent continuity equations so that the resulting set of equations can be solved algebraically. In contrast to SIM-I, SIM-II makes no restriction on the number of unknown link flows; therefore, it must employ a formal optimization procedure and a suitable objective function to solve the equations. For the optimization routine, SIM-II utilizes the Out-of-Kilter Algorithm to find that set of link flows that minimizes the energy costs for pumping throughout the system.

In both SIM-I and SIM-II, the problem formulation outlined above applies only to those nodes and links that are a part of transfer subsystems[6]. The gravity subsystems, which contain the remainder of the links and nodes, do not require pumping and consequently they are treated differently. Water that enters these subsystems is considered to be stored in reservoirs and no releases are permitted unless (1) the reservoir is full or (2) there is a downstream demand that cannot otherwise be met.

Reservoir Operating Rules

Reservoir operating rules relate the fraction-full of an individual reservoir to the fraction-full of the entire

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[6] The reader is referred to the Appendix for a definition of transfer and gravity subsystems.

transfer subsystem. Letting p_{jk} denote the fraction-full of reservoir j in time period k, these rules are expressed as:

$$p_{jk} = \begin{cases} P_k + f_{jk} P_k \; ; & \text{if } 0 \leq P_k \leq 0.5 \\ P_k + f_{jk} (1-P_k); & \text{if } 0.5 < P_k \leq 1.0 \end{cases}$$

where

f_{jk} = rule coefficient for reservoir j in time period k, and

P_k = fraction-full of the transfer subsystem, in time period k.

Using these rules, the storage contents at the end of the time period, $S_{j,k+1}$, can be predicted as:

$$S_{j,k+1} = p_{jk} V_j$$

where V_j is the capacity of reservoir j. With the ending storage contents predicted from the rules and the beginning storage contents available from the solution for the previous time period, the storage terms are no longer variables in either of the two simulation programs.

These rules permit storage to be allocated amongst reservoirs or to be redistributed in time. For example, the storage contents of upstream reservoirs can be kept less than that of the downstream reservoirs for flood control purposes or the seasonal storage levels can be manipulated to buffer canal pumping requirements.

Before proceeding with a specific example to illustrate the use of reservoir operating rules it is appropriate to describe briefly the physical interpretation of the coefficients, f_{jk}, and to point out some limitations in their application. A reservoir with a coefficient of 0.0 would, by definition, be at the same fraction-full as the entire system of reservoirs. A coefficient of 0.20 would indicate that when it was physically possible, the reservoir so designated could be filled to a level 20 percent greater than the system as a whole. For example, a reservoir with a rule coefficient of 0.20 could be allowed to be 60 percent full when all storage capacity in the system is only half utilized. If the coefficient was -0.20 then the reservoir would be 40 percent full when the system was at half capacity.

To insure that storage levels do not exceed available reservoir capacity and do not become negative, rule coefficients must be within the limits:

$$-1.0 \leq f_{jk} \leq 1.0$$

To prevent inadvertent inconsistencies in rules for individual reservoirs as compared to the system as a whole, the following condition must also be satisfied:

$$\sum_{j=1}^{n} f_{jk} V_j = 0$$

where V_j is the capacity of reservoir j.

A simple example will further illustrate the physical meaning of operating rules as they are employed by SIM-I and SIM-II. Figure 13 shows the monthly rule coefficients for a reservoir, an annual history of the fraction-full of the entire system, and the annual history of the fraction-full of the reservoir as computed from the rules and capacity utilized in the system. During the year the rule coefficients ranged from +1.0 to -1.0; and the total system varied from 40 percent to 70 percent full. The total system is shown to be filling during the first 6 months, declining in utilized capacity for 4 months, and then filling again during the last 2 months.

Using the coefficients and total system content illustrated, the reservoir storage levels can be found from the rules. The resulting relative storage levels are shown in Figure 13. The reservoir is shown to be filling during the first 3 months, followed by a minor drop, filling again, and then experiencing a major decrease in storage which empties the reservoir for 2 months, followed by another filling period. The filling periods prepare the reservoir for the large April and August demands that the reservoir must satisfy.

Rules such as those illustrated in this example can either be arbitrarily selected or obtained from studies of system operation. The Allocation Program which is described in Chapter VI provides a means for deriving a set of rules for a system, operating under conditions of average demands and average streamflows, which will minimize energy costs for pumping.

Inputs and Demands

As mentioned earlier, both simulation programs handle many details of the simulation identically, including inputs and demands. Demands, D_{jk}, from any node, either a reservoir or junction, are specified by input and, if possible, satisfied. If a shortage occurs during any time period, it is noted; a cumulative deficit is computed and kept for reference.

Reservoir evaporation losses, E_{jk}, are computed using monthly evaporation rates and the surface area of the reservoir at the beginning of the time period. Surface area is calculated from a second order polynomial that represents the area-capacity curve for the reservoir. Evaporation losses from canals, which are based on monthly evaporation rates and an assumed canal surface area, are removed from the system at the nearest node.

Import requirements, I_{jk}, are also computed at the beginning of each time period and are based on the difference between supply and demand for the upcoming month and are made contingent on the availability of an import supply. Imports are subject to several restrictions; specifically, imports are

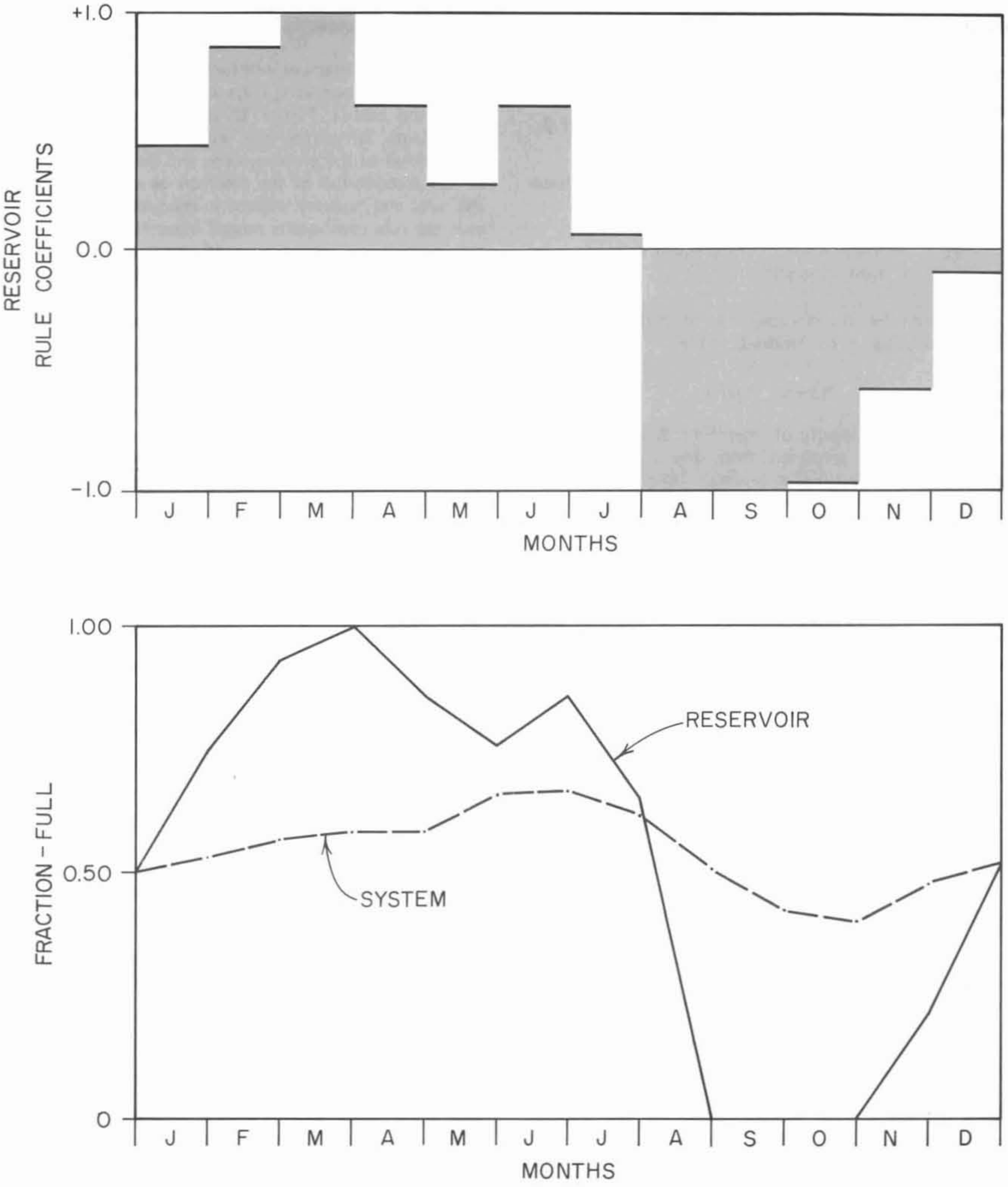

Figure 13

RELATIONSHIP BETWEEN TOTAL SYSTEM STORAGE AND INDIVIDUAL RESERVOIR STORAGE

- not permitted until all reservoirs are built,
- not allowed if spills would occur,
- permitted only at one node, and
- less than or equal to a specified limit.

Unregulated inflows into each node, U_{jk}, must be known for all time periods. These inflows can be an observed historical sequence, these same events reordered, or a synthetic sequence generated through the techniques of stochastic hydrology.

Program Differences

Model Equations

The network configurations and the solution techniques required to solve the resulting set of equations constitute the major differences between the simulation programs.

Rewriting the general formulation of the simulation equation as given earlier, but abbreviating all the known terms by b_{jk}, results in

$$\sum_{i=1}^{m} A_{ji} \, Q_{ik} = b_{jk} \qquad j = 1,\ldots,n$$

where

$$b_{jk} = \frac{(S_{j,k+1} - S_{jk})}{\Delta t} + D_{jk} + E_{jk} - U_{jk} - I_{jk}.$$

Both simulation programs solve this general set of equations. The difference in the specific equations solved by the two programs is mainly in the number of flow variables, Q_{jk}. This is, however, a very big difference. In SIM-I the number of variables is reduced so it equals the number if independent continuity equations, n-1. This permits a direct algebraic solution. SIM-II, on the other hand, retains all the flow variables in the problem and an optimization technique is required to obtain a solution.

The physical interpretation of this difference is relatively simple. Consider the water resource system illustrated in Figure 6a (page 21). This system consists of two river basins with four river reaches and seven pump-canals. Three of these pump-canals interconnect the two river basins. Also the system contains four reservoirs and two non-storage nodes. There are, for this system, eleven flow variables and six continuity equations. SIM-II accomodates this system directly.

SIM-I, on the other hand, requires elimination of connecting links until the number of flow variables equals the number of independent equations. This situation occurs when the system is reduced to a tree-shaped structure; that is, no loops are retained. To reduce the example system illustrated in Figure 6a to a tree-shaped structure shown in Figure 6b, SIM-I would have to eliminate two "real" pump-canals and to add one "dummy" pump-canal, which represents the possible flow path from node 4 to node 1.

SIM-I is not as restricted in application as this example might lead one to believe. The manner in which SIM-I solves the resulting equations and interprets the solution actually relieves many of the limitations imposed by the tree-shaped structure.

When such a set of equations is solved algebraically, in the manner indicated above, there is no direct control exerted over the sign (direction) of the resulting flows. However, this condition carries certain advantages. Since between two nodes two links per flow variable may be considered, it is possible to use this property to accommodate the case where storage elements (nodes) are connected by both river reaches and pump-canals. While both may not function simultaneously in SIM-I, it is possible to describe the case where pumping upstream may occur over part of the year and downstream releases may occur over the remainder. Also, the case of flow in either direction in a pump-canal can be treated. Finally, it is possible with this property of SIM-I to determine the reasonableness of a prejudgment by the planner that only a pump-canal or a river reach, not both, should link two nodes.

The four cases of major interest with respect to the sign convention adapted are:

CASE	(+)	(-)
1. →	pump-canal	river reach
2. →	pump-canal	pump-canal
3. →	pump-canal	
4. →	river reach	

A pump-canal and a river reach (case 1) can occur together whenever an upstream pumping capability is provided in a river basin between nodes. Flow both ways in a pump-canal (case 2) is a likely possibility where interbasin transfers are to be accommodated and the pumping capacity for two-way flow is planned. If pumping facilities are to be provided for one-way flow only and no river reach for flow in the opposite direction exists (case 3), indicated flows must be positive for the solution to be feasible. Similarly, if only a river reach is provided (case 4), flow must be positive (downstream).

The infeasible solutions for cases 3 and 4 (negative flow against the direction of pumping or negative flow upstream in a river reach) can occur with SIM-I if:

- the problem as originally posed was not a correct statement of the prototype structure, or

- the reservoir operating rules are not compatible with the reduced physical system.

In the first instance it may be necessary to add more links. This may be done only if it does not violate the general rule that the number of equations must equal the number of unknowns. Otherwise, one must utilize an optimization technique such as provided in SIM-II. In the second instance it may be necessary to return to the Allocation Program to determine a set of operating rules which are compatible with the system as structured for SIM-I.

Because the equation set for SIM-I is solved algebraically no limits are placed on flows which may result. The solution which is obtained corresponds to an "unconstrained" optimization solution such as might be provided by SIM-II if all constraints were relaxed. In effect, such a solution merely recognizes the necessity of the tree-shaped structure utilized by SIM-I in which all looping has been eliminated. Some guidance in the identification of the tree-shaped structure which should be utilized by SIM-I (since many are possible) can be obtained by a trial run on SIM-II.

The planner must exercise some judgment also in this tradeoff between the solution techniques. Ideally, he should have SIM-I operational on a structure which corresponds as nearly as possible to the unconstrained solution produced by SIM-II. This will give him maximum flexibility and reasonable cost for examining the many hundreds of possibilities which may be worthy of study in the early phases of the planning exercise. Then, if he wishes to impose additional conditions he can do so by moving to SIM-II and to the Allocation Program and sustaining a somewhat higher computation cost.

SIM-I Solution Technique

The formulation of the equation set for SIM-I is:

$$\sum_{i=1}^{n-1} A_{ji} Q_{ik} = b_{jk} \quad ; \quad j = 1,\ldots,n-1$$

which can be expressed in matrix notation as

$$A\,Q = b$$

where

A = a matrix of coefficients that indicate the direction of link flow with respect to a node; +1 is assigned for inflow, -1 for outflow, and 0 for links not connected to the node.

Q = a vector of flow variables, and

b = a vector of known quantities that are obtained from mass balances at each node in the system.

The solution for the unknown flow variables, Q, is:

$$Q = A^{-1}\,b$$

where A^{-1} = the inverse of the A matrix.

SIM-II Solution Techniques

SIM-II overcomes two of the weaknesses in SIM-I. It relaxes the limitation of a tree-shaped system configuration and, as a result, is capable of analyzing any system structure. As a consequence the number of flow variables will be greater than the number of independent continuity equations. SIM-II also has the ability to limit both the magnitude and direction of all flow variables. This is accomplished by placing lower and upper bounds on all flows, which increases the size of the problem to be solved. To solve this problem an objective function and an optimization technique are required. SIM-II has an objective to minimize energy costs for pumping and uses the Out-of-Kilter Algorithm, an optimization procedure from network flow theory, to solve the problem.

Mathematically, the SIM-II problem can be stated for a single time period, k, as:

$$\text{minimize } Z = \sum_{i=1}^{m} C_{ik}\, Q_{ik}$$

subject to

$$\sum_{i=1}^{m} A_{ji}\, Q_{ik} = b_{jk} \quad ; \quad j = 1,\ldots,n$$

and

$$L_{ik} \leq Q_{ik} \leq U_{ik} \quad ; \quad i = 1,\ldots,m$$

where

C_{ik} = unit cost of pumping in link i during time period k,

L_{ik} = lower limit of flow in link i during time period k, and

U_{ik} = upper limit of flow in link i during time period k.

All other terms are as previously described.

The first expression simply states that the objective of the procedure is to find the minimum-cost flow values in a system where C_{ik} describes the cost of pumping a unit quantity of water Q_{ik}, through link i in time period k. It is explicit in this objective function that the pumping cost is linearly dependent on the quantity of water being pumped. This implies that the pumping lift is constant throughout the time period (normally a 1-month period is used) and that this can be expressed by the lift that exists at the beginning of the time period.

The second set of equations comprise a set of constraints that require continuity to be maintained at every node. These equations have been previously described. The last set of equations represents the upper and lower constraints on the flow variables. Upper bounds, U_{ik}, of any size may be placed on the flow in any link. Lower bounds are usually, but not necessarily, zero.

Transforming the water resource system problem into a network flow problem and solving it with the Out-of-Kilter Algorithm constitute the most formidable tasks. These are accomplished in the same manner in SIM-II as in the Allocation Program described in the next chapter. The reader is referred to that chapter for the finer points of problem formulation, and to the literature (Durbin and Kroenke, 1967; Fulkerson, 1961; Ford and Fulkerson, 1962) for details of the Out-of-Kilter Algorithm.

Data Requirements

Almost all of the data required to operate both simulation programs are found on the common input data tape described in Chapter VII. The unique features of each program do, however, require certain additional data.

Both SIM-I and SIM-II require a set of parameters controlling the detail of the output desired, the number of river basins involved, and the import node. The order of the reservoir-river routing system in each basin, lists of all elements in the ultimate system, and two vectors giving the construction times for the reservoirs and canals are also required. In addition, SIM-I needs a matrix that describes the tree-shaped network to be investigated. No additional data are required by SIM-II.

Capabilities

Both simulation programs describe the hydraulic behavior of the system under a given set of hydrologic inputs and demands. They differ in the manner of problem description. SIM-II describes the prototype system accurately and uses an optimization technique to produce the "minimum-cost" hydraulic behavior. SIM-II is more realistic of the prototype than SIM-I, but this purer representation is gained only at a substantial increase in computational costs. SIM-I, because it is a low-cost computational program, is an ideal investigative tool for the staging analysis, where a high degree of precision may not be required. The decision as to which model to use depends on the resources available to the analyst and the accuracy of solution required.

VI. ALLOCATION PROGRAM

Purpose

The Allocation Program provides the planner with a rigorous means for evaluation of alternative water resource systems. It includes a formal optimization technique, the Out-of-Kilter Algorithm, and is free of many of the limitations embodied in SIM-I and SIM-II that were needed in the earlier planning steps where these programs are used to keep the cost of analysis low. The Allocation Program provides the most realistic representation of the behavior of the actual physical system, but it does so at added computational cost. Hence, although the Allocation Program is employed in Phase I of the analysis, its greatest application will occur in the later phase of planning when the number of alternatives has been greatly reduced.

The general purposes of the program are:

- to evaluate alternative water resource development plans,
- to estimate average reservoir operating rules which can be utilized in SIM-I and SIM-II, and
- to find reservoir and canal sizes which correspond to superior alternatives.

Concepts

General

The Allocation Program uses the Out-of-Kilter Algorithm to find a solution to the system optimization problem exemplified by the above general purposes. The Out-of-Kilter Algorithm is an optimization technique derived from network flow theory which has the capability to solve problems which can be stated in terms of flows and costs as:

$$\sum_i q_{ij} - \sum_i q_{ji} = 0 \qquad ; \qquad j = 1,\ldots,N$$

$$L_{ij} < q_{ij} < U_{ij} \qquad ; \qquad \text{all } ij$$

$$\text{Minimize } z = \sum_{ij} q_{ij} \; C_{ij}$$

where

q_{ij} = flow form node i into node j,

q_{ji} = flowout of node j into node i,

L_{ij} = lower limit of flow, q_{ij},

U_{ij} = upper limit of flow, q_{ij}, and

C_{ij} = cost of transferring one unit of flow, q_{ij}.

Each of the specific problems that must be treated by the Allocation Program—finding element sizes, estimating reservoir rules, and evaluating plans—were formulated in these terms. A network structure, uniquely required for the solution algorithm, was devised to represent the space and time continuum for which the optimal solution was desired. This structure and the mathematical statements which characterize it are described below.

Network Structure

First, the physical system must be represented by a node-link configuration as described in the Appendix. Figure 14 illustrates an example of such a configuration. It consists of six nodes (four reservoirs and two non-storage link junctions), and eleven links (seven canals and four river reaches). A necessary condition is that all reservoirs that do not have a river reach leaving them must have an outlet for spilling outside of the network any excess water that enters them. Thus, spills leaving the network are no longer considered available for use.

Next, since this node-link configuration is only a spatial representation of the problem, it must be expanded to include time considerations. This is accomplished by introducing a more general space-time linkage, an *arc*, which allows flows to be carried from one state in time to another. Arcs are used to represent all elements that can transfer water through the network—in either time or space, including links, which represent canals or river reaches. Nodes are used, as in SIM-I and SIM-II, to portray the reservoirs and non-storage link junctions. Seven special-purpose nodes, which will be described shortly, are introduced to permit structuring of the continuous closed network required by the solution technique.

For each time period in the problem, there exists a particular node-link configuration that must be connected to the preceding and following configurations by reservoir storage arcs. This time-space representation of the problem can be envisioned as a layered network, each layer representing time period. Figure 15 illustrates how the typical node-link system of Figure 14 would be expanded to cover four time periods within the planning horizon.

This expanded network of nodes, links and arcs, which we will call the *system network* must be modified

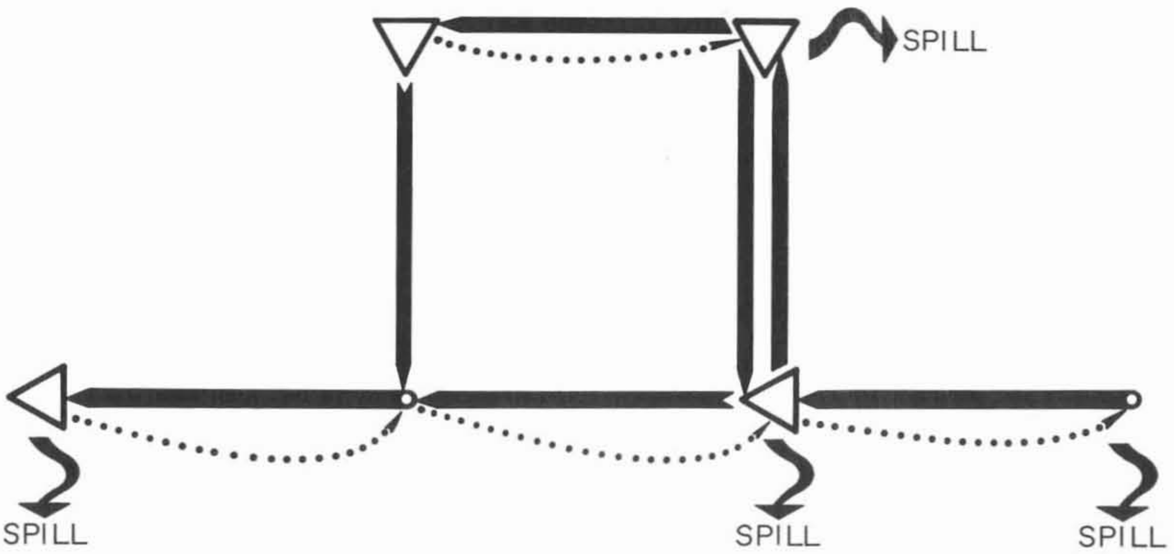

FIGURE 14.–TYPICAL NODE-LINK CONFIGURATION

still further. Initial reservoir storage contents must be provided for; inputs and demands must be accommodated; spills must be allowed to leave the system; and, at the end of the problem, provisions must be made for the final reservoir storage contents. These requirements were met by adding certain special arcs and nodes. Finally, in order to make the system continuous over time and space, a node to accommodate net balance was added and this was connected to the other supplemental nodes. The completed continuous network, built around the system network depicted in Figure 15, is represented conceptually in Figure 16.

The flow of water through the system network proceeds generally as follows: The initial storage contents are set at an *initial storage* node for all reservoirs that are available for use in the first time period and are transferred into the system through a set of arcs. Inputs to and demands from the system occur through arcs that are connected from special *inputs* and *demands* nodes to every node in the system network, including both reservoirs and non-storage junctions. If a system node's input is greater than its demand, the difference between them is transferred to the system network through an input arc. The opposite is true when the demand is the larger quantity.

Imported water enters the system network from an *imports* node through a set of arcs, one for each time period, that are connected to the same reservoir. Also, all reservoirs from which spills can occur must have an arc leaving them for each time period and connecting to a *spills* node. The storage contents at the end of the last time period leave the system network through a set of arcs, one for each reservoir, and terminating in a *final storage* node. Finally, to make the entire network continuous, a necessary condition for network theory, the *net balance* node is provided. This node is connected by appropriate arcs to six of the special nodes–inputs, imports, demands, spills, initial storage, and final storage. No storage is provided in the net balance node, a condition for total continuity of the problem.

The total number of nodes, N_n, in the continuous network outlined above is given by:

$$N_n = [L \times n_n] + 7$$

where L is the number of time periods in the problem, n_n is the number of nodes in the spatial representation of the problem (reservoirs plus non-storage nodes included in the system network), and 7 is the number of special nodes. For the problem represented by Figure 15 (six nodes and four years) the total number of nodes in the problem would be 31.

Ten types of arcs are identified for the continuous network. Flow in each of these is subject to constraints within limits as summarized in Table 4.

Flow in river arcs is normally permitted to vary between zero and a specific upper limit; however, lower limits can be raised, for example, to provide for quality control or to guarantee prior rights to appropriated water. Canal flows and reservoir storage contents are likely to be constrained between zero and some design capacity which may be predetermined or, as a condition for minimizing cost, may itself be a part of the problem solution. Upper limits may be stipulated as zero for elements not available for service and the limit raised to storage capacity when each element is added.

Initial reservoir storage contents, inputs, and demands are forced in the system by setting upper and

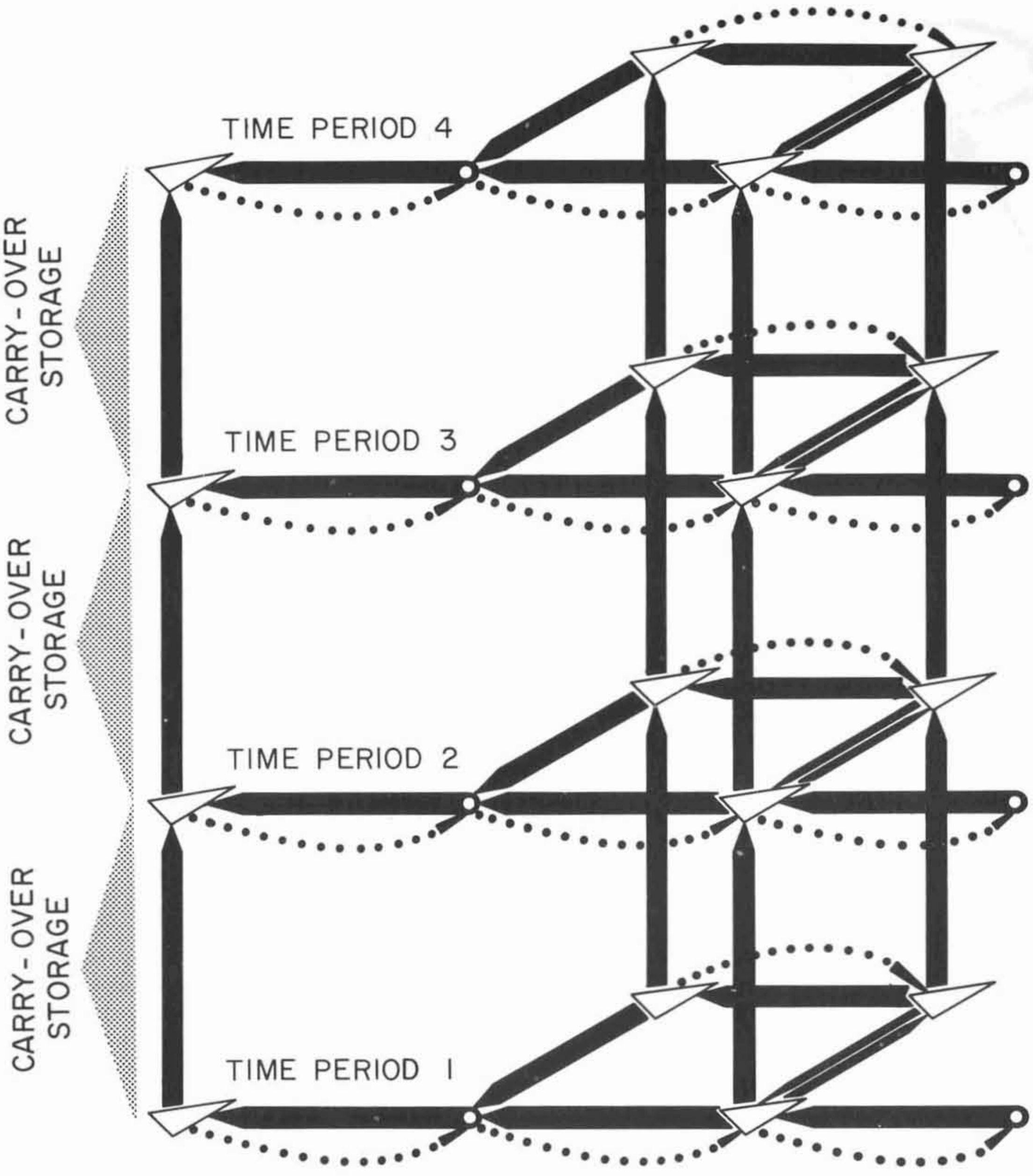

FIGURE 15.–SYSTEM NETWORK FOR A PROBLEM COVERING FOUR TIME PERIODS

lower bounds identical. (A tacit assumption is that evaporation losses can be estimated, a priori). Imported water is limited between zero and the maximum available, the upper limit being flexible to account for variability with season or the conditions of water purchase. Flows in spill arcs are limited between zero and the maximum capacities of spillways or outlet works.

Flow in the final storage arcs is normally limited to be within the range of zero and the actual capacities of reservoirs. However, for very large systems and/or long planning horizons it may be practical, for reasons of computer capacity or cost, to span the entire planning period. It may then be necessary to treat a succession of shorter problems, overlapped in time so as to give a reasonable representation of the larger problem. For example, suppose it is desired that the Allocation Programs span only four years of a longer problem. The program can be used first to solve the four-year problem at the beginning of the planning period, and considering the first-year solution as valid, moved up to span the second through fifth years, and so on. A succession of solutions provides all of the information needed for practical optimization, but care must be exercised in setting appropriate limits for the final contents of

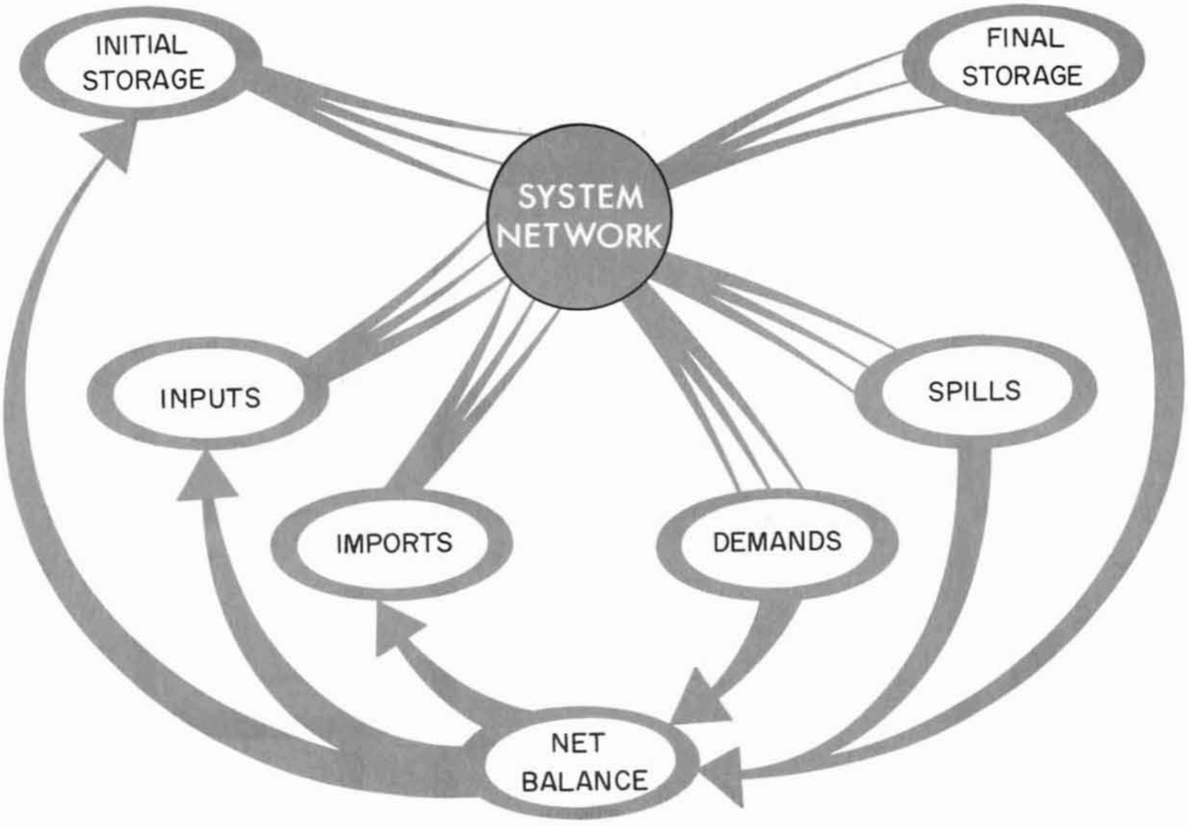

FIGURE 16.–CONTINUOUS NETWORK FOR THE ALLOCATION PROBLEM

reservoirs in the intermediate solutions. Experience has shown that reservoir capacities can be used as upper limits, but that lower limits must be regulated by the condition that

$$\text{Lower Limit} = S_o (k)^n$$

where S_o is the reservoir storage capacity, k is a coefficient representing the permissible annual drawdown rate, and n is the number of years spanned by the network. Selection of k is a matter involving some judgment based on experience, since it affects the relative dependence of the system on in-basin storage and sources of imported water. A value of k of about 0.8 has been satisfactory for the work reported here.

The net balance arcs, whose flows must be in accord with total continuity for the problem, are limited by the sums of their component flows. For example, the limits on total storage are simply the sums of the limits on the individual initial storage arcs.

The total number of arcs, N_a, in the continuous network is given by

$$N_a = [(n_L + n_n + n_s + 1) \times L] + 6$$

where n_L is the number of links (canals plus river reaches), n_n is the number of nodes (reservoirs plus non-storage junctions), n_s is the number of nodes from which spills can occur, 1 represents the single import arc in each time period, L is the number of time periods in the problem, and 6 represents the number of net balance arcs. For the problem represented by Figure 15 (11 links, 6 nodes, 2 spill nodes, and 4 years) the total number of arcs would be 86.

Mathematical Description

The mathematical structure of the Allocation Program is designed by three sets of constraint equations and an objective function. One set of constraint equations requires that continuity be satisfied at all nodes in the network. The remaining two sets of equations describe the upper and lower limits on flow in all arcs in the network. Thus, there is one equation for each node and two equations for each arc. (For the illustrative example of Figure 15, there would be 203 equations [31 + (2 x 86)].

Table 4.—Arc Types, and Definitions of Their Lower and Upper Bounds

	ARC TYPE		LOWER BOUND	UPPER BOUND
1.	River		Zero	River Capacity
2.	Canal		Zero	Canal Capacity
3.	Storage		Zero	Reservoir Capacity
4.	Initial Storage		Initial Storage	Initial Storage
5.	Input		Net Input	Net Input
6.	Demand		Net Demand	Net Demand
7.	Import		Zero	Maximum Available
8.	Spill		Zero	Maximum Permissible
9.	Final Storage		$S_o(k)^n$	Reservoir Capacity
10.	Net Balance			
	a.	Total Initial Storage	Σ Initial Storages	Σ Initial Storages
	b.	Total Inputs	Σ Inputs	Σ Inputs
	c.	Total Imports	Zero	Σ Maximum Imports
	d.	Total Demands	Σ Demands	Σ Demands
	e.	Total Spills	Zero	Σ Maximum Spills
	f.	Total Final Storage	Σ Final Storages	Σ Reservoir Capacities

Table 5.—Definition of Terms in the Mathematical Description of the Allocation Program

Q_{ijk} = flow from node i to node j in time period k

Q_{jik} = flow from node j to node i in time period k

P_{jk} = spills from node j in time period k

$\theta_j = \begin{cases} 1 \text{ if node j is a spill node} \\ 0 \text{ if node j is not a spill node} \end{cases}$

S_{jk} = storage contents of reservoir (node) j at the beginning of time period k

Δt = time interval

I_k = amount of water imported

$\delta_j = \begin{cases} 1 \text{ if node j is the import node} \\ 0 \text{ if node j is not the import node} \end{cases}$

$\beta_{jk} = D_{jk} + E_{jk} - U_{jk}$

D_{jk} = demands from node j in time period k

E_{jk} = evaporation losses from node j in time period k

U_{jk} = unregulated inflow to node j in time period k

χ_o = total initial storage contents entering the system

$\phi_{jk} = \begin{cases} 1 \text{ if } \beta_{jk} \text{ is negative} \\ 0 \text{ if } \beta_{jk} \text{ is positive} \end{cases}$

χ_i = the sum of all negative β_{jk}'s (net inputs)

χ_d = the sum of all positive β_{jk}'s (net demands)

χ_m = the sum of all imported water

χ_s = the sum of all water spilled

χ_f = the sum of all final reservoir storage contents

n_r = number of reservoirs

n = number of reservoirs and non-storage junctions

L = number of time periods in the problem

Using the terminology defined in Table 5, continuity equations for the nodes listed previously can be written as:

1. Reservoir Nodes

$$\sum_i Q_{ijk} - \sum_i Q_{jik} - \theta_j P_{jk} - \frac{S_{jk+1}}{\Delta t} + \frac{S_{jk}}{\Delta t} + \delta_j I_k + \beta_{jk} = 0$$

$$j = 1,2,\ldots,n_r$$

$$k = 1,2,\ldots,L$$

2. Link Junction Nodes

$$\sum_i Q_{ijk} - \sum_i Q_{jik} - \theta_j P_{jk} + \delta_j I_k + \beta_{jk} = 0$$

$$j = n_r + 1,\ldots,n$$

$$k = 1,2,\ldots,L$$

3. Initial Storage Node

$$\sum_{j=1}^{n_r} \frac{S_{j1}}{\Delta t} - X_o = 0$$

4. Inputs Node

$$\sum_{k=1}^{L} \sum_{j=1}^{n} \phi_{jk}\, \beta_{jk} - X_i = 0$$

5. Demands Node

$$\sum_{k=1}^{L} \sum_{j=1}^{n} (1 - \phi_{jk})\, \beta_{jk} - X_d = 0$$

6. Imports Node

$$\sum_{k=1}^{L} \sum_{j=1}^{L} \delta_j I_k - X_m = 0$$

7. Spills Node

$$\sum_{k=1}^{L} \sum_{j=1}^{n} \theta_j P_{jk} - X_s = 0$$

8. Final Storage Node

$$\sum_{j=1}^{n_r} \frac{S_{j,L+1}}{\Delta t} - X_f = 0$$

9. Net Balance Node

$$X_o + X_i - X_d + X_m - X_s - X_f = 0$$

All of these equations are of the common form required by the Out-of-Kilter Algorithm, which can be stated as

$$\sum_i q_{ij} - \sum_i q_{ji} = 0, \qquad j = 1,\ldots,N$$

In this basic equation q_{ij} represents the flow from any node, i, into node j; and q_{ji} is the flow out of node j into any other node, i. Flows entering and leaving a node occur, of course, only through the arcs connected to it.

Flows in these arcs are constrained to be within a range defined by the arcs' lower and upper limits. These constraints can be expressed as

$$q_{ij} \geq L_{ij}, \text{ and}$$

$$q_{ij} \leq U_{ij}.$$

(The reader is referred again to Table 4 for descriptions of limits applied to each of the 10 types of arcs.)

The objective function to be satisfied in solving these equations is to minimize the cost of transferring water through the network. This is expressed as:

$$\text{Minimize } Z = \sum C_{ij}\, q_{ij}.$$

In the network structure used as an example in this chapter (Figures 14, 15, and 16), pump-canal arcs are the only type which have costs associated with them, i.e., real costs of transport are associated only with pumping situations. However, as a device to prevent unnecessary spills, a small penalty cost of $0.001 per cfs per month was assigned to water spilled from the system.

The reader should note that the objective function, as stated, is only flow dependent; it presumes a fixed pumping head. Consequently, a unit cost per cfs pumped must be assumed.

Using the concepts outlined above, the Allocation Program, with the Out-of-Kilter Algorithm[7] as its basic solution technique, obtains a solution for the network that minimizes water transfer costs while satisfying inputs to and demands from the system.

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[7] Details of the Out-of-Kilter Algorithm are not presented in this report. Interested readers are referred to the literature (Durbin and Kroenke, 1967; Fulkerson, 1961; Ford and Fulkerson, 1962).

Special Input Requirements

The standard input data tape described in Chapter VII meets nearly all of the input data requirements for the Allocation Program. Additional data needed but not on this tape include:

- the number of years the network can span,
- the number of years in the problem,
- the nodes from which spills can occur,
- the maximum permissible spills, and
- the years in which the canals and reservoirs are placed in service.

When reservoir and canal sizes are being sought, trial values are also input data.

Capabilities

The Allocation Program is used in Phase I of the planning sequence to estimate canal and reservoir sizes and to find reservoir operating rules. In Phase IV, the final step in the approach outlined in Chapter III, it is used to evaluate and improve alternative development plans. In performing these functions, the Allocation Program solves minimum-cost network flow problems that are quite similar. They differ only in the time period spanned by the network and in the values used for inputs and demands. The following subsections present these differences and describe how a single program provides these seemingly diverse capabilities.

Canal and Reservoir Sizing

The determination of preliminary canal and reservoir sizes involves the evaluation of a series of trial element sizes using the Allocation Program to predict the system's performance and to assess its cost. Each successive set of trial sizes is based on the results of the preceding sets that have been evaluated. The process of successive trials continues until the reduction in the project cost is small. It should be recognized that the sizes resulting from this exercise would be preliminary and would be further improved in Phases II, III, and IV of the planning sequence.

The process of improving element sizes is guided mainly by marginal energy costs, which are products of a solution with the Allocation Program. By definition, marginal cost for a canal or reservoir occurs only when flow or storage is at the design level. It is the change energy cost that results for an element if the element size is changed by one unit of flow (canal) or by one unit of storage (reservoir). Marginal costs for energy for an element may normally be expected to increase as that element's size is forced downward since the water which cannot be accommodated must pass along a more expensive route to its ultimate destination.

The sizing process usually begins by setting the element sizes abnormally high so that no marginal costs are incurred, i.e., the solution is unconstrained. The element sizes are then reduced until their marginal energy costs just become non-zero. When this occurs, the elements are performing under conditions close to optimal design levels, at least part of the time. Next, the sizes of elements are reduced until the increasing marginal energy costs become equal to the decreasing marginal capital costs. This condition is the terminating point for the optimization process used in Phase I. High ratios of maximum to mean canal flows and high variability in storage levels characterize the solution.

An alternative terminating point is to stop the process when no further significant reductions in total project cost can be achieved. However, since energy costs are incurred in each time interval and capital costs occur only once, the two cost items are not directly comparable. With a system that experiences increasing demands over time, total energy cost for each time period should be accumulated and discounted to its present worth before it is compared with total capital costs. This would be an expensive computational procedure for large systems, and consequently, it is not considered appropriate in this preliminary phase of the evaluation process.

A recommended procedure, commensurate with the preliminary aspects of Phase I, is to size initially the canals and reservoirs under some assumed design conditions and to refine them in the latter phases of planning. For example, one could find preliminary canal sizes under conditions of average hydrology and maximum demand. Reservoir sizes, on the other hand, could be estimated initially for extreme hydrologic and demand conditions. The period spanned by the network for this analysis should be kept short, preferably a few years. This process does not assure that the resulting sizes are the smallest possible. Such refinement must be deferred until the final evaluation of those plans surviving the screening process.

Reservoir Operating Rules

The Allocation Program estimates average reservoir operating rules for each season of the year and for each reservoir, using average streamflows and demands. The reservoir and canal sizes used are those found in the sizing process. Initial reservoir storage contents and lower limits on the final storage levels must be estimated. The time period spanned by the network is kept relatively short; a period of 2 or 3 years has been found satisfactory for this purpose.

The minimum-cost solution provides reservoir storage levels for each time period in the problem. To approximate average conditions the seasonal storage values for the year in the center of the period spanned are converted to a set of rules which can then be used in SIM-I and SIM-II.

Evaluate Alternative Development Plans

To evaluate an alternative development plan for the given system the planner must investigate the cost of operation and capital investment for canals and reservoirs and the sequence of reservoir and canal construction. The Allocation Program provides information pertinent to each of these considerations.

The planner begins with a basic description of the network to be studied, defining the link-node configuration of the physical system and the length of the planning period. Reservoir and canal capacities and import restrictions are identified as the major constraints. A set of inflows and return flows are specified as inputs, while projected water usage and evaporation losses constitute demands.

The network flow problem thus stipulated is then solved to find a minimum-cost operating plan. By definition, this plan represents, for the conditions imposed, the least costly way of transferring water through the network to meet all stipulated demands.

If additional refinement in the canal and reservoir sizes or their construction timing is desired, this can be accomplished with the Allocation Program. Marginal energy and capital costs can be used to improve element sizes and to refine the schedule for placing them in service. If a canal or a reservoir that has not been placed in service is found to have a zero marginal energy cost, there is a high likelihood that its construction can be deferred. In these instances construction should probably be delayed as long as the total present worth of the project continues to decrease. For reservoirs and canals that are already in service, conservation storage allocation should progressively be decreased until the total present worth of the project ceases to change.

With some experience in using the Allocation Program, the planner can progressively revise and refine the superior alternative water development plans until he is convinced that no further significant cost reductions can be achieved. There is no automatic and foolproof procedure for guaranteeing a minimum-cost solution, but it is believed that the methodology outlined in the previous chapters, and culminating in use of the Allocation Program to evaluate attractive alternatives, enhances the prospect enormously over the traditional planning approaches.

VII. DATA MANAGEMENT

Objective

A planned system of data management is indispensable for organizing, verifying, and preparing in suitable form the very large quantities of data required by the simulation and optimization programs described in Chapters IV, V, and VI. To aid in accomplishing this objective of adequate data preparation, four computer programs have been developed. They are:

- CURFIT-I
- TAPEWRITE-II
- UPDATE-I
- PORTGEN-I

Program Purposes

These four programs are designed to insure the proper generation of a single comprehensive tape file capable of supplying input to the simulation and optimization programs. Concurrent with tape file development, printed reports can be generated that provide verification of successful processing.

Basically, these programs consist of coded instructions for computer processing of data cards which contain information originally prepared by the user on problem-oriented input data forms. Upon reading the data cards, and upon appropriate user request, the programs perform various data-editing tasks. This is done prior to the performance of programmed data manipulations, computations, preparation of printed reports, or loading of the results onto magnetic tape. Individually, these programs function as follows:

CURFIT-I is a curve-fitting program that fits a polynomial equation, of up to ninth order, to a set of x and y data points. The results of this curve-fitting process are printed for manual review prior to their use in TAPEWRITE-II.

TAPEWRITE-II is the program that generates the comprehensive tape file for use by the simulation and optimization programs. The input to this program is a set of cards that contains most of the data required by these programs. In general, the data include: problem title data; program and problem analysis control parameters; system configuration data; cost and capacity information for all reservoirs and canals; and seasonal runoff, evaporation, demand, and reservoir operating rule data. A more comprehensive list of the data requirements is contained in the following section of this chapter.

UPDATE-I is a program that has the capability to update the comprehensive tape file developed by TAPEWRITE-II. This allows the user to make minor changes to the tape file without regenerating the entire file. UPDATE-I and TAPEWRITE-II use the same problem-oriented input data forms.

PORTGEN-I is a report generating program that prints, in an organized manner, the contents of the tape files generated by TAPEWRITE-II and UPDATE-I.

Although these four programs are used separately, they are intended to function as an integrated set to ease the user's tasks of preparing and verifying data for use in the simulation and optimization programs. The manner in which they relate to each other and the user is depicted in Figure17.

Data Requirements

The purpose of this section is to itemize and describe, in detail, the data contained on the common input tape. From a user's and TAPEWRITE-II computer processing viewpoint, the data are grouped into five categories; the following descriptions are categorized accordingly:

TITLE DATA.—a maximum of up to four cards of title data is contained on the first part of the data tape. This permits the user to identify each version of his input tape and helps to avoid incorrect usage of tapes.

TYPE 1 DATA.—Fifteen program control and problem analysis control data variables on seven Type 1 Data Cards are input to TAPEWRITE-II. These data describe:

- the number of reservoirs, junctions, pump-canals, and river reaches within the system;
- the number of years of data contained on the tape as well as the calendar year that corresponds to the first year of that data;
- the number of the reservoir or junction at which water can be imported;
- the number of seasons (analysis time increments—normally months per year);
- the interest rate, repayment period, reservoir financing lag time, and pump-canal financing lag time used to calculate present worth costs of capital investment and the operation and maintenance cost;
- the unit cost of water at the import point; and

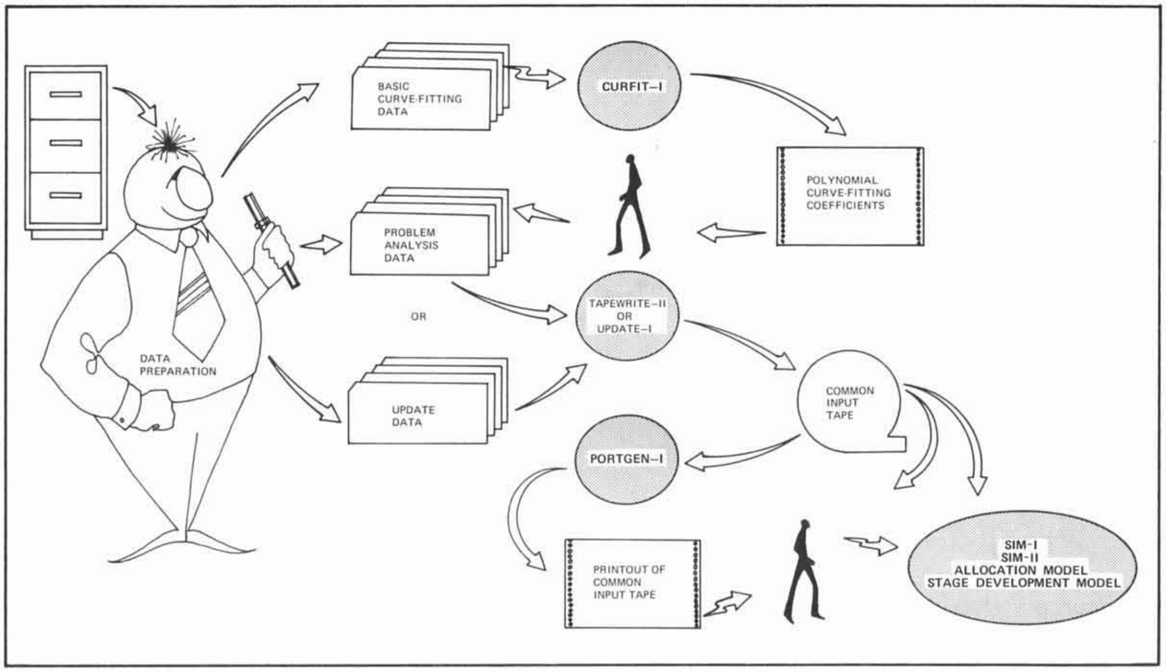


FIGURE 17.–INTERRELATIONSHIPS OF DATA MANAGEMENT PROGRAMS

the annual operation and maintenance cost for reservoirs, and the operation, maintenance, and replacement costs of pump-canal facilities, both as percentages of their total capital costs.

TYPE 2 DATA.–System configuration data describing the correspondence of reservoirs and junctions to pump-canals and river reaches constitute this type of data. This included:

- the junctions and/or reservoirs at the ends of each pump-canal; and
- the junctions and/or reservoirs at the ends of each river reach.

TYPE 3 DATA.–This type of data consists generally of cost and capacity data for reservoirs and canals, specified demands for water, and the amount of water available for import. Specifically the data include:

- the maximum annual amounts of water that are available for import for each year;
- seasonal import coefficients that describe the percentage of the maximum annual import quantities that is available for import in each of up to 12 seasons;
- the annual composite demand for water (irrigation, municipal, and industrial) for each reservoir and junction specified and for each year;
- the unit cost of energy (dollars per kilowatthour) for pumping during each of up to 12 seasons;
- pump-canal maximum capacities, and river reach maximum capacities, in cfs;
- pump-canal pump lift data that specify the average lift from one junction to another, for use solely in the Allocation Model;
- data that specify the elevation of the highest ridge point for each pump-canal;
- second-order polynomial coefficients that describe the capital cost-capacity relationships for each pump-canal;
- third-order polynomial coefficients that describe the area-capacity relationships and elevation-capacity relationships for each reservoir;
- maximum storage capacities and initial storage contents (percent full) of all reservoirs; and
- estimates of the average annual surface area of each reservoir.

TYPE 4 DATA.—These data consist of the following seasonal data:

- unregulated inflow into each reservoir for each year contained on the tape and for up to 12 seasons per year;
- demand coefficients for each reservoir and for up to 12 seasons that represent the percentage of the annual demand required in each season of the year;
- reservoir operating rules for each reservoir and season of the year; and
- gross evaporation and rainfall data, or only net evaporation data, for each reservoir and season of the year.

These data are organized for input to both TAPEWRITE-II and UPDATE-I on a series of problem-oriented input data sheets. Figure 18 shows a typical example of these input data sheets. A complex set of these sheets along with an example problem are given in Volumes III through V of the project completion report.

Curfit-I Program Description

CURFIT-I's sole capability is to fit a polynomial equation of first to ninth order and of the form

$$y = c + a_1 x^1 + a_2 x^2 + \dots\dots\dots + a_n x^n$$

to a series of x and y data points. CURFIT-I is used with the other programs described herein to develop second-order polynomial coefficients that relate pump-canal costs to their capacities. Also, it is used to develop third-order polynomial coefficients that relate reservoir surface area and elevation to reservoir conservation storage contents.

This program was acquired through the Center for Research in Water Resources at The University of Texas at Austin, Texas, and was revised to meet the user-oriented data preparation specifications established for the data management programs.

As it is now structured, CURFIT-I is capable of fitting a curve to as many as 100 x and y data points. Also, it can perform up to 20 orders of fit on a given set of data points in a single processing run. The data points, as supplied to CURFIT-I, need not be in any pre-specified order since they are automatically sorted in ascending order by the program. The program then generates the output reports containing the curve-fitting coefficients, the x and y data points on which the curve fitting was performed, the order of fit for which coefficients were computed, and other data concerning the "goodness of fit."

Tapewrite-II Program Description

TAPEWRITE-II is designed to read a set of problem-oriented input data cards that are in a somewhat unspecified sequence and then generate a comprehensive tape file for use by the simulation and optimization programs.

From a user's viewpoint, the problem-oriented input forms are structured in a manner to group the input data by type and processing similarities into the five categories itemized earlier in this chapter. These data categories evolved for two reasons. First, the data within each category have somewhat common characteristics. For example, all seasonal data except demand coefficients are in the Type 1 category. The second reason is that, from a computer processing viewpoint, all cards within a category are read using a single format. Thus, the cards within each data category, with one exception, can be supplied to the computer in a random sequence. The exception involves the Type 4 data category where flow (unregulated streamflow) data must be the last to enter the computer.

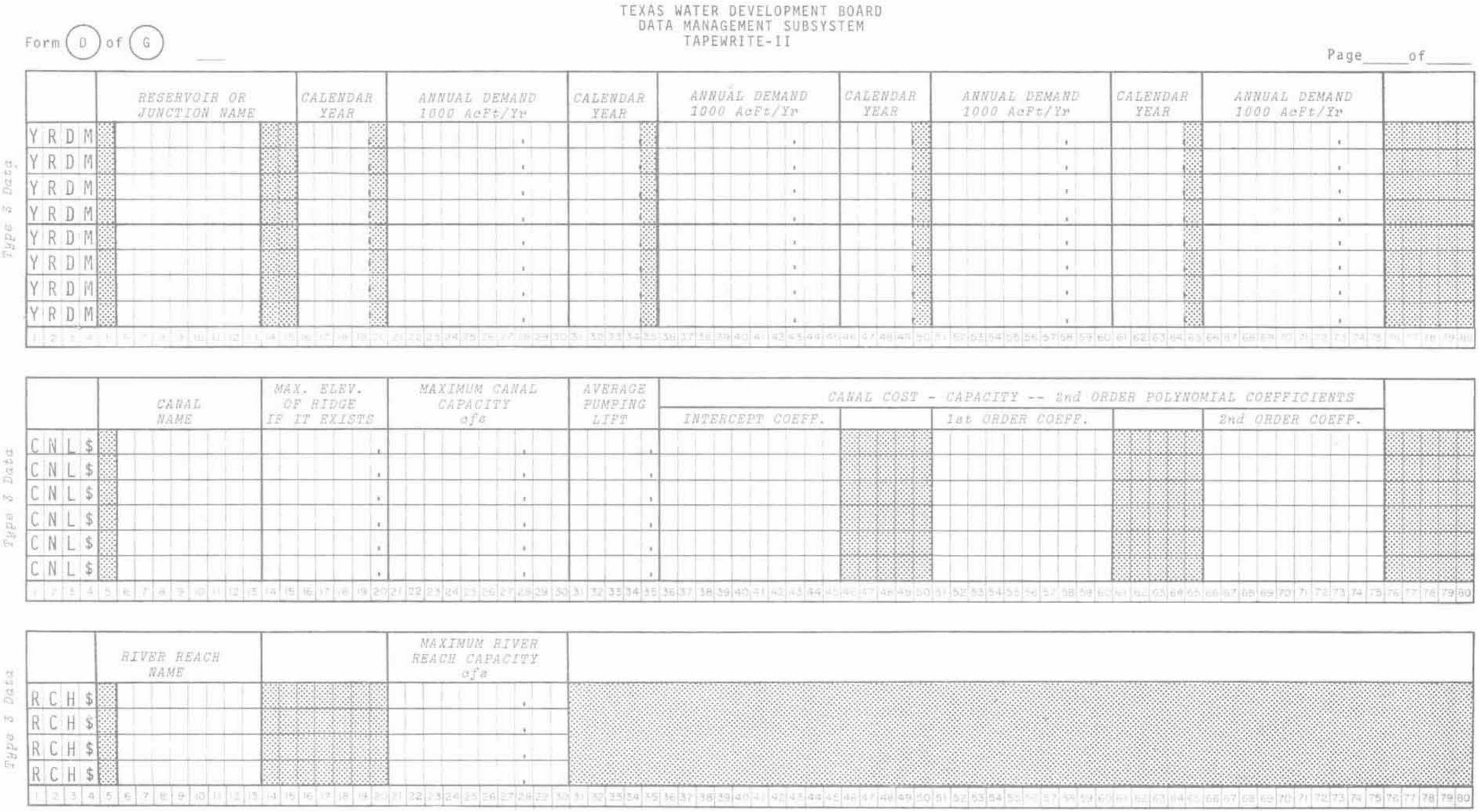
Also, from a user's viewpoint, each of the data card types has its unique problem-oriented identifier. For example, as shown in Figure 18, the card type containing the annual demands for water for each reservoir and junction and for each year on the tape has the card identifier "YRDM." Similarly, the card type containing pump-canal cost capacity data has the identifier "CNL$." Other typical identifiers are "IMPORT/YEAR," "POWER COST," "CANAL FINANCE LAG TIME =," and "EVAP." The computer uses the first four letters in each of the identifiers to uniquely identify a card type. Proper identification causes the computer to branch to a computer coded instruction that assigns the identified data to the proper variable to be loaded onto magnetic tape.

This problem-oriented data entry concept provides the user with some flexibility within each data category, yet provides sufficient rigidity to insure that the data are entered in the proper order.

The primary output of TAPEWRITE-II is the common input data tape required by the simulation and optimization programs; however, the program also generates, upon user specification, a listing of the cards as they were entered into the computer, error messages that identify errors and inconsistencies in the user-supplied data, and, when incorporating the PORTGEN-I program discussed below, a report displaying the contents of the tape generated.

Update-I Program Description

UPDATE-I was designed to read the tape files generated by either TAPEWRITE-II or this program and



TEXAS WATER DEVELOPMENT BOARD
DATA MANAGEMENT SUBSYSTEM
TAPEWRITE-II

Form (D) of (G)

Page_____of_____

Type 3 Data

	RESERVOIR OR JUNCTION NAME	CALENDAR YEAR	ANNUAL DEMAND 1000 AcFt/Yr	CALENDAR YEAR	ANNUAL DEMAND 1000 AcFt/Yr	CALENDAR YEAR	ANNUAL DEMAND 1000 AcFt/Yr	CALENDAR YEAR	ANNUAL DEMAND 1000 AcFt/Yr	
YRDM			.		.		.		.	
YRDM			.		.		.		.	
YRDM			.		.		.		.	
YRDM			.		.		.		.	
YRDM			.		.		.		.	
YRDM			.		.		.		.	
YRDM			.		.		.		.	
YRDM			.		.		.		.	

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80

Type 3 Data

	CANAL NAME	MAX. ELEV. OF RIDGE IF IT EXISTS	MAXIMUM CANAL CAPACITY cfs	AVERAGE PUMPING LIFT	CANAL COST - CAPACITY -- 2nd ORDER POLYNOMIAL COEFFICIENTS					
					INTERCEPT COEFF.		1st ORDER COEFF.		2nd ORDER COEFF.	
CNL$		.	.	.						
CNL$		.	.	.						
CNL$		.	.	.						
CNL$		.	.	.						
CNL$		.	.	.						
CNL$		.	.	.						

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80

Type 3 Data

	RIVER REACH NAME		MAXIMUM RIVER REACH CAPACITY cfs	
RCH$			.	
RCH$			.	
RCH$			.	
RCH$			.	

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80

Figure 18

EXAMPLE OF INPUT DATA SHEETS USED FOR THE TAPEWRITE-II COMPUTER PROGRAM to make changes to the files without regenerating the entire original file.

Specifically, UPDATE-I reads both the tape file to be updated and data cards containing update information. The update information contained on the input cards replaces the variables to be updated, and the computer then generates a new tape file containing the updated data and the unchanged data. Each time the UPDATE-I program is used, a new tape file is generated and the old tape file is preserved.

The computer program designed to accomplish this is almost identical to TAPEWRITE-II. The major difference is the order in which the various computer tape "read and write" instructions are performed.

From a user's viewpoint, UPDATE-I uses the same input sheets as TAPEWRITE-II; however, UPDATE-I does not have the capability to change any of the data on system configuration (Type 2 data) or uncontrolled flow. All other data can be updated. In order to change the system configuration or flow data, a new tape must be developed using TAPEWRITE-II. From a user and computer data entry viewpoint, UPDATE-I has the same restrictions regarding order of input card data as TAPEWRITE-II, but contains no editing features.

Portgen-I Program Description

The primary purpose of PORTGEN-I is to list the contents of tape files for user inspection and to assure that the file has the proper data. Secondarily, it is used to provide a convenient data display for identifying what data items need to be changed or updated prior to using the UPDATE-I program.

PORTGEN-I was designed to be used by itself or as a part of TAPEWRITE-II. In both capacities it was structured to print the contents of tape files generated by TAPEWRITE-II and UPDATE-I. As it is now structured, PORTGEN-I requires no card input data. The tape to be printed is the only input used. Similarly, no data manipulation, editing, or computation is performed.

Data Management Output

The principal product of the data management effort as it relates to the planning process is a standardized input tape which carries most of the general information needed by the simulation and optimization programs described in the three previous chapters. This tape may be continuously updated, revised, and supplemented as best serves the goals of the planner in using the programs. It serves as an essential building block for the planning process and for the ensuing research and development tasks designed to further enhance overall planning capability.

VIII. A TEST OF PLANNING TECHNIQUES

Concept of the Test

The research reported here was concerned primarily with the development and adaptation of certain advance tools and techniques to facilitate planning of complex water resource systems. It was performed in an atmosphere that included the real planning problems facing the planners of the Trans-Texas Division of the Texas Water Plan. To an important degree the planning approach which was evolved was shaped by these real problems—sizing of elements of the system, finding realistic operating rules, screening many alternative system configurations, and scheduling for least costly development over a 50-year planning horizon. The approach was devised specifically to followthe planner's logic and to anticipate his need for assistance in the decision process at a critical points along the way.

It is appropriate that the planning approach suggested here, developed with the Trans-Texas Division in the minds of the researchers be tested on this system and in a way which corresponds as closely as possible to the real world of the planner. The test should accomplish the following:

- It should confirm the logic of the planning process as it applies to large-scale, complex water resource systems such as the Trans-Texas Division.
- It should demonstrate the operational capability of the programs which have been developed as planning tools.
- It should give guidance to the planners and researchers concerning:
    - program capabilities and limitations,
    - basic data requirements and deficiencies,
    - relative costs of utilizing the several components of the planning package, and
    - areas where additional research and development beyond the scope of the present project are needed.

The actual process of applying the planning tools developed in this project on a full-scale basis to the Texas Water Plan is far from a trivial undertaking. It could not possibly be undertaken within the project itself, nor should it have been since the project's aim was one of developing the capability, not presuming the role of the planner. Moreover, the very pragmatic considerations of time and funds forced the formulation of a more modest test, one that could actually be accomplished with the resources available, at the same time assuming that the goals contained above could be reached.

The test problem selected is a realistic one, identified with the Trans-Texas Division of the Texas Water Plan. To a certain degree, appropriate to the goals of the test, that system has been slightly modified and some assumptions have been introduced where they were considered effective for the purposes of a test. Since this would be the normal process for a planner, as he proceeds to evaluate the many alternatives possible, the introduction of assumptions or simplifications does not violate the planning logic. Wherever these steps have been taken, they are documented and discussed so that their consequences will be clear to the reader.

The Test Problem [8]

System Configuration

The physical system selected for the test varies slightly from the configuration proposed for the Trans-Texas Division illustrated in Figure 2 (page 13). It is represented schematically by the node-link network of Figure 19. This network consists of 24 nodes, of which 18 are reservoirs and 6 are non-storage junctions, and 42 links, including 30 pump-canals and 12 river reaches. Each node and link in the system is identified by number, and in the coding system used for the programs it is further identified by those elements to which it is connected.

The facilities embraced by the system, featuring the Trans-Texas Canal, would span about 500 miles across the entire State of Texas and would convey water from the basins of surplus in East Texas—the Lower Red, Sulphur, Cypress Creek, and Sabine—to the High Plains of West Texas. Provision would be made for supplementing in-state supplies after 1985 with imported water from the Mississippi River. On the system selected for the test, it has been assumed that imports could be introduced through the Cypress Creek Basin at Caddo Lake, designated as Node 16 in Figure 19. For the purposes of the test, the terminous of the system was taken as Bull Lake in the High Plains, although under the Texas Water Plan, water could ultimately be conveyed as well to the Trans-Pecos area, El Paso, and to New Mexico. Along its route the Trans-Texas Canal would deliver water in the Dallas-Fort Worth area as well as to North Central Texas.

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[8] The test data used do not necessarily represent exact Trans-Texas Division planning conditions; therefore, no conclusions for design or operation of that system should be made from these discussions.

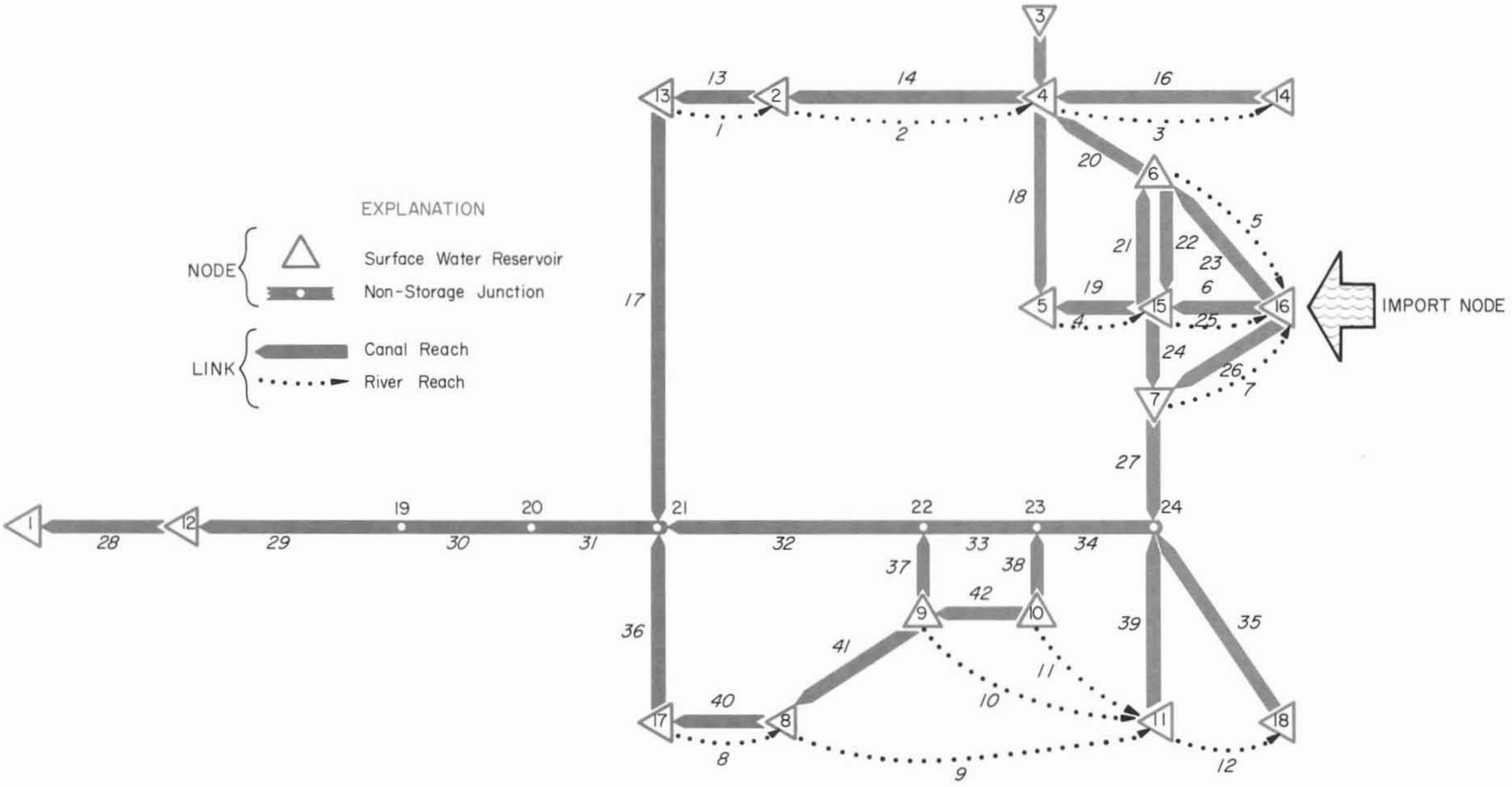

Figure 19

SCHEMATIC REPRESENTATION OF THE TRANS-TEXAS RESERVOIR - RIVER - CANAL SYSTEM

Test Period

Of the 18 reservoirs included in the test system only five, represented by nodes 14 through 18, presently exist. The others, designated as nodes 1 through 13, would be added to the system as required to meet demands. Until 1985, in-basin supplies are considered adequate by the Texas Water Development Board to meet anticipated demands; subsequently, facilities would have to be added to transport surplus water from the eastern basins to water deficient areas further west. Ultimately, importation of water from outside the state would have to be initiated. Before the year import is required, reservoirs 1 to 13 would have to be added; all would have to be in place before importation could begin. Four of these reservoirs would have to be available by 1985 to meet anticipated demands in the planning period, 1985 to 2020. The remaining nine reservoirs will be staged after 1985.

For purposes of the test problem, the planning period of interest begins in 1985 when the first new facilities in the Trans-Texas Division would have to be in place and ready for service, and it extends through the year 2020, a period of 36 years. Imported water is allowed to enter the system only after all reservoirs and canals needed to convey water to the terminal reservoir (node 1) at Bull Lake have been constructed. This restriction guarantees that the full potential of in-state water resource development would be realized before importation.

Hydrologic Conditions and Demands

The 36-year hydrologic sequence of unregulated inflows to the reservoirs comprising the test system was developed from historical records. It includes an actual historical sequence of 17-years duration in the middle of the planning period and two segments at either extreme made up of randomly selected values from the 17-year record. The inflow pattern which resulted is shown in Figure 20. It corresponds to a mean annual inflow over the 36-year period of 8.9 million acre-feet with the annual inflows ranging from 4.5 million to 17.5 million acre-feet.

It is acknowledged that the hydrological sequence, although composed of observed quantities, is an arbitrary one which does not preserve all of the statistical properties which would be preferred from a more rigorous hydrologic viewpoint. The reader will recall, however, that the present research is aimed at development of simulation and optimization techniques, not at exploring the hydrologic sensitivities of the decision process. This extremely important consideration is reserved for subsequent research efforts in which the programs developed in this effort are expected to figure prominently. It must suffice for the test of program capability to constrain the hydrology of the problem to this admittedly arbitrary pattern until such time as better hydrologic sequences can be made available.

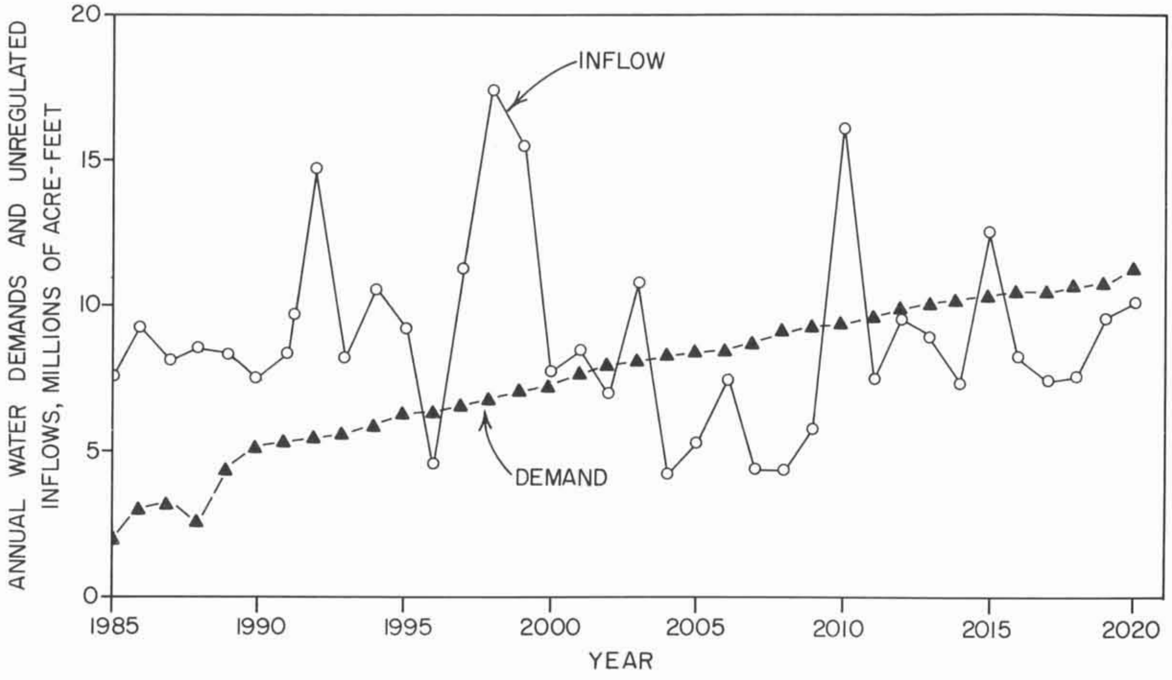

FIGURE 20.–UNREGULATED INFLOWS* AND WATER DEMANDS USED IN THE DEMONSTRATION PROBLEM

* NOT INCLUDING IMPORT

Annual water demands projected for municipal, industrial, and agricultural uses through 2020 were prepared for each node in the network. A set of seasonal coefficients was used to distribute the annual demands to monthly values. The average annual demand imposed in the entire test system was about 7.6 million acre-feet per year, varying from 2.2 million to 11.2 million acre-feet per year over the 36-year period studied. Demands for water in the basins of origin are included in the pattern illustrated in Figure 20[9]. West Texas deliveries which must be transported through the Trans-Texas Canal are expected to be about 10 million acre-feet in the year 2020, according to estimates of the Texas Water Development Board (1968).

Deficits, Spills, and Losses

The combined storage capability of the test system of 18 reservoirs is estimated by the Texas Water Development Board to be 16,788,000 acre-feet, of which approximately 3,823,000 acre-feet is for existing reservoirs and the balance would be developed in the new reservoirs. Table 6 summarizes storage capacities of individual reservoirs in the system.

Seven reservoirs in the system, represented by nodes 3, 8, 9, 10, 11, 17, and 18, are located in the network in such a way that they cannot receive supplemental supplies by importation, i.e., links are not provided to permit flow from the import supply node 16. Consequently, if water demands and exports plus losses at these reservoirs exceed available storage plus inflows, deficits will occur. The only way they can be offset in solution of the planning problem is to assume that demands will be curtailed accordingly.

Downstream releases can occur in all reservoirs of the system but these do not, in all cases, return to the system. In six reservoirs, nodes 1, 3, 12, 14, 16, and 18, downstream releases are assumed to be permanently lost and classified as "spills." For reason of their function as terminal storage facilities and because negligible inflow occurs, nodes 1 and 12 would probably not be expected to spill.

Evaporation losses were based on estimates of average monthly evaporation rates for each reservoir site (Lowry, 1960). These losses generally amounted to about 10 percent of the unregulated inflows.

Table 6.—Available Reservoir Storage Capacity

NODE	CONSERVATION STORAGE CAPACITY (THOUSANDS OF ACRE-FEET)	NODE	CONSERVATION STORAGE CAPACITY (THOUSANDS OF ACRE-FEET)
1	1,000	10	215
2	750	11	420
3	370	12	1,800
4	2,220	13	273
5	460	14	803
6	3,500	15	377
7	775	16	136
8	370	17	907
9	622	18	1,600

Application of Programs To The Test Problem

The program application sequence set forth in Chapter III includes four major phases:

I. Initial Element Sizing and Reservoir Operating Rules

II. Initial Screening

III. Secondary Screening

IV. Final Screening

In each of these phases, specific applications of the simulation and optimization programs were suggested. This pattern was followed generally in the test of program capability on the system selected for study. A few departures from the more comprehensive evaluation of alternatives which the planner would normally carry out were necessary at selected points in the testing process. These, and their consequences in the planning exercise, are described fully in the ensuing discussion of program applications.

Phase IA—Initial Element Sizing

A significant portion of the cost to construct, operate, and maintain the Trans-Texas Division of the Texas Water System will be attributed to the conveyance facilities, the canals and pump stations[10]. Costs are

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[9] The reader will note a dip in the demand curve at the year 1988. This is the result of keypunch error which dropped the demand for that year by 1 million acre-feet.

[10] Analysis of relative costs of the various elements of the system studied showed that the total capital cost of reservoirs was generally less than one quarter that of canals. For this reason, the sizing exercise was concentrated on canals and the capacities of reservoirs were regarded as fixed.

closely related to the size of the facility and to the variability of flows which must be accomodated; hence, measures to reduce flows, particularly in the larger and longer canals of the system, and to bring fluctuations within smaller limits should be effective in reducing costs. The Allocation Program, applied early in the planning sequence, provides a means of exploring the effectiveness of such measures.

As a first step in canal sizing, it is necessary to solve the network problem without any capacity restraints. This solution, known as the "unconstrained solution," identifies those canals where flows are large or highly variable over the year. Subsequently, steps in canal sizing were directed toward driving the capital cost of canals downward, using average flows and average maximum to mean flow ratios for all canals as crude indices of the effectiveness of imposing constraints.

The test problem was solved with the Allocation Program using a 2-year span (24 months in the network) for the unconstrained case and four constrained conditions. The solutions, summarized in Tables 7, 8, 9, and 10, were all based on average hydrology and ultimate (2020) water demands. Final storage levels were based on an annual draft on reservoirs not to exceed 20 percent of beginning-of-year capacity. Reservoirs were started in a half-full condition [11]

Table 7 presents a summary of maximum canal flows which resulted from the five solutions of the problem. Several features of these results are noteworthy. First, it will be seen that some flows are zero in all five cases, conveying the impression that certain canals are not needed. For *average hydrologic conditions* this may be true, but later analysis will show that these canals are needed and that flows under more realistic operating conditions are non-zero in all links. Second, some canal flows are quite high in the unconstrained solution; in fact, a few were found to be quite unrealistic when compared to values chosen for preliminary design of some of the canals in the proposed system. A good example is that of link 17 where the unconstrained maximum flow of 22,990 cfs was subsequently constrained to 3,600 cfs as a more realistic estimate of maximum canal capacity for this location in the real system.

Table 8 presents a summary of ratios of maximum to mean flows, i.e., measures of flow variability. It will be noted here that the constraints imposed on links 13, 14, and 17, for example, greatly reduce flow variability. This, in addition to reduction in flows, should contribute to cost savings in these elements, although flow increases could be experienced for other canals in the system, in links 25, 26, and 27, for example.

The general result of imposing constraints is exemplified by the averages of maximum flows and flow ratios. In both tables these are seen to be driven downward as adjustments are made in the constraints. While these indices are admittedly crude, they seem consistent with the argument that such adjustments, for the system studied, will lead to lower overall cost. This presumption if borne out by the trend in canal construction costs illustrated for the five cases in Table 9. An unconstrained solution resulted in annual canal construction costs of about $142 million, while imposition of capacity constraints in selected canals forced the costs down to $102 million in the fourth trial. A small increase in energy costs was experienced as constraints were imposed and flows were forced to take more expensive routes, in terms of pumping costs, through the system. These should probably be offset in a more detailed cost analysis by savings in fixed costs of pumping facilities by virtue of the reduction in variability of flows.

Table 10 indicates the tradeoffs between capital cost savings and the increased energy costs that result from capacity constraints. For example, in the case of link 17, constraining the flow to 3,600 cfs, although saving $400 per cfs per year, resulted in a marginal energy cost of $2,760 per cfs per year. By relaxing the constraint, i.e., allowing greater flow in link 17, it would have been possible through a number of trials to save $2,360 per cfs per year for this link. This shift was made, in fact, in the fourth case in which the constraint on link 13 was tightened, in effect reducing the marginal cost of pumping link 17 to $50 per cfs per year. Further adjustments could have been made, perhaps, with some minor improvement in total cost. In practice, the planner may wish to proceed further with certain details, but for the purpose of testing the technique the fourth trial was considered sufficient.

Results of the canal sizing exercise can also be useful in preliminary sizing of reservoirs. It is apparent that increasing the size of reservoirs, at added cost, may be compensated for by reduced canal flow variability, hence, lowering costs for the canals supplying them. Some insight into this tradeoff can be gained by examining the marginal costs of canals for selected reservoirs in the system. An example from the test problem is node 12, a reservoir within the High Plains area near the terminal demand point. This reservoir is supplied entirely from the storage lower in the system through link 31, a major canal.

Figure 21 illustrates how the capacity of reservoir 12 and link (canal) 31 are related for 2020 conditions and average hydrology. At the stipulated capacity of 1.8

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[11] The reader will note that these conditions are discretionary with the planner and will affect the results of the sizing exercise. The examples given are to illustrate the effect on total project cost of imposing capacity restraints, but the procedure may also be used to explore conditions of hydrology demand, and reservoir operation. The results obtained in Phase I, it will be remembered, are preliminary and subject to revision in later phases of the planning sequence.

Table 7.—Unconstrained and Constrained Maximum Canal Flows for the Test Problem (cfs)

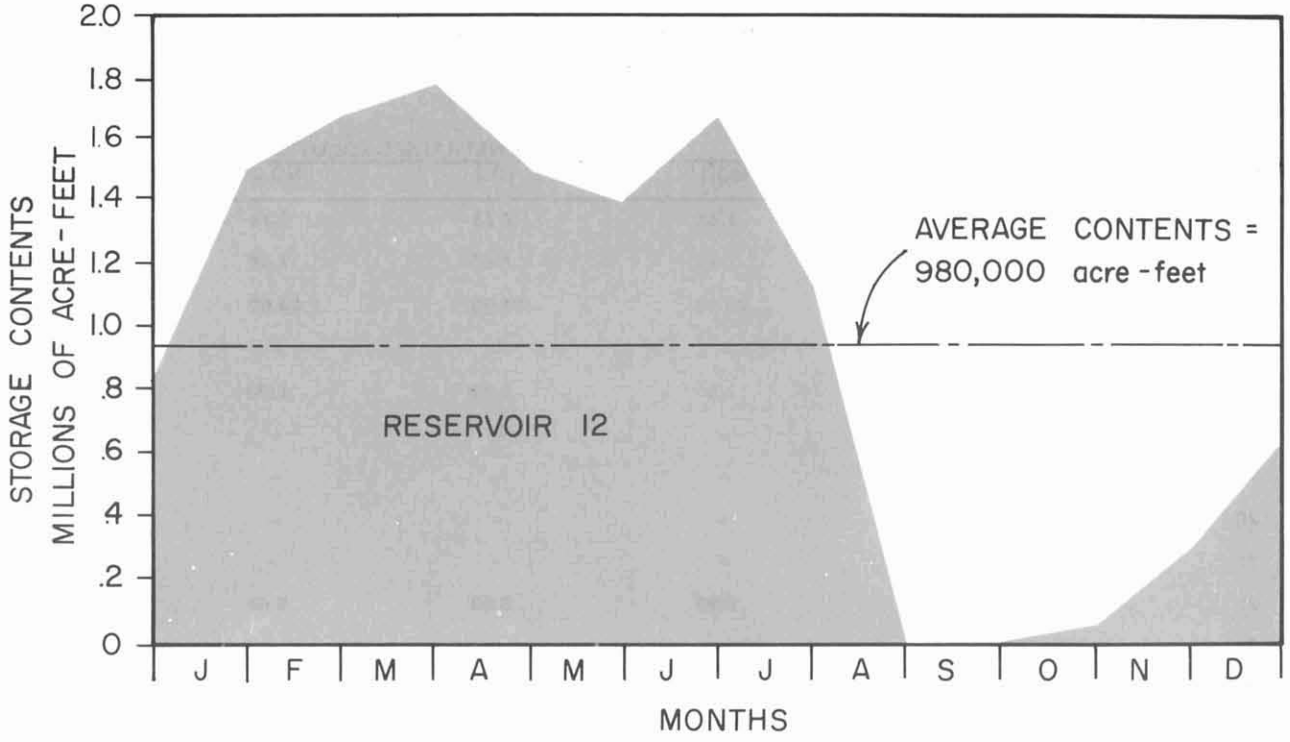
LINK	UNCONSTRAINED SOLUTION	CONSTRAINED SOLUTIONS* NO.1	NO.2	NO.3	NO.4
13	24,140	*4,000*	*4,000*	*4,000*	*3,400*
14	20,270	*4,000*	*4,000*	*4,000*	*3,000*
15	2,690	880	880	880	*250*
16	4,000	0	0	0	0
17	22,990	*3,600*	*3,600*	*3,600*	*3,600*
18	1,000	0	0	0	0
19	0	0	0	0	0
20	3,170	0	0	0	0
21	0	0	0	0	0
22	0	3,670	2,010	2,970	2,240
23	0	0	0	0	0
24	7,240	*7,400*	6,370	5,890	7,400
25	2,460	*12,000*	*12,000*	*12,000*	*12,000*
26	3,070	*12,000*	*12,000*	*12,000*	*12,000*
27	8,660	*12,000*	*12,000*	11,970	*9,000*
28	0	0	0	0	0
29	35,710	20,570	17,480	17,500	17,500
30	36,770	20,930	17,860	17,860	17,860
31	36,290	21,150	*18,000*	*18,000*	*18,000*
32	25,260	*15,000*	*12,000*	*12,000*	*12,000*
33	25,260	*15,000*	*12,000*	*12,000*	*12,000*
34	25,260	*15,000*	*12,000*	*12,000*	*12,000*
35	16,580	14,390	*6,000*	*3,000*	*3,000*
36	5,440	4,180	2,420	3,540	3,540
37	0	1,110	1,180	*500*	*500*
38	430	1,400	1,400	*500*	*500*
39	150	3,470	4,830	*3,000*	*2,500*
40	20	1,580	3,320	*1,000*	*1,000*
41	0	0	930	350	*500*
42	0	0	0	0	0
Average Maximum Flows	14,000	9,180	7,550	7,200	7,000

* Italic type indicates the maximum flow is equal to the capacity constraint.

Table 8.—Ratios of Maximum to Mean Flows for the Test Problem

LINK	UNCONSTRAINED SOLUTION	CONSTRAINED SOLUTIONS*			
		NO.1	NO.2	NO.3	NO.4
13	3.06	*1.15*	*1.15*	*1.16*	*1.00*
14	2.86	*1.45*	*1.45*	*1.46*	*1.11*
15	2.80	24.00	24.00	24.00	*4.96*
16	2.93	–	–	–	–
17	2.91	*1.00*	*1.00*	*1.00*	*1.01*
18	12.42	–	–	–	–
19	–	–	–	–	–
20	11.74	–	–	–	–
21	–	–	–	–	–
22	–	6.97	3.83	5.65	4.27
23	–	–	–	–	–
24	5.74	*2.87*	*2.40*	*2.18*	*2.98*
25	3.62	*9.42*	*8.86*	*8.58*	*10.16*
26	2.95	*4.60*	*4.74*	*4.35*	*3.97*
27	3.22	*2.17*	*2.17*	2.06	*1.54*
28	–	–	–	–	–
29	2.63	1.55	1.32	1.31	1.31
30	2.64	1.53	1.31	1.30	1.30
31	2.58	1.53	*1.30*	*1.30*	*1.30*
32	4.95	*1.59*	*1.28*	*1.28*	*1.28*
33	4.95	*1.63*	*1.30*	*1.30*	*1.30*
34	5.01	*1.66*	*1.32*	*1.33*	*1.32*
35	7.12	5.65	*2.26*	*1.32*	*1.31*
36	5.17	5.30	2.78	4.07	4.07
37	–	5.09	8.54	*3.60*	*3.60*
38	7.82	7.46	7.73	*2.67*	*2.67*
39	7.15	3.65	5.12	*3.14*	*2.66*
40	8.00	7.22	11.12	*3.34*	*3.34*
41	–	–	11.76	4.47	*6.28*
42	–	–	–	–	–
Average Ratio	5.09	4.64	4.85	3.68	2.85

* Italic type indicates the canal constraint was in effect.



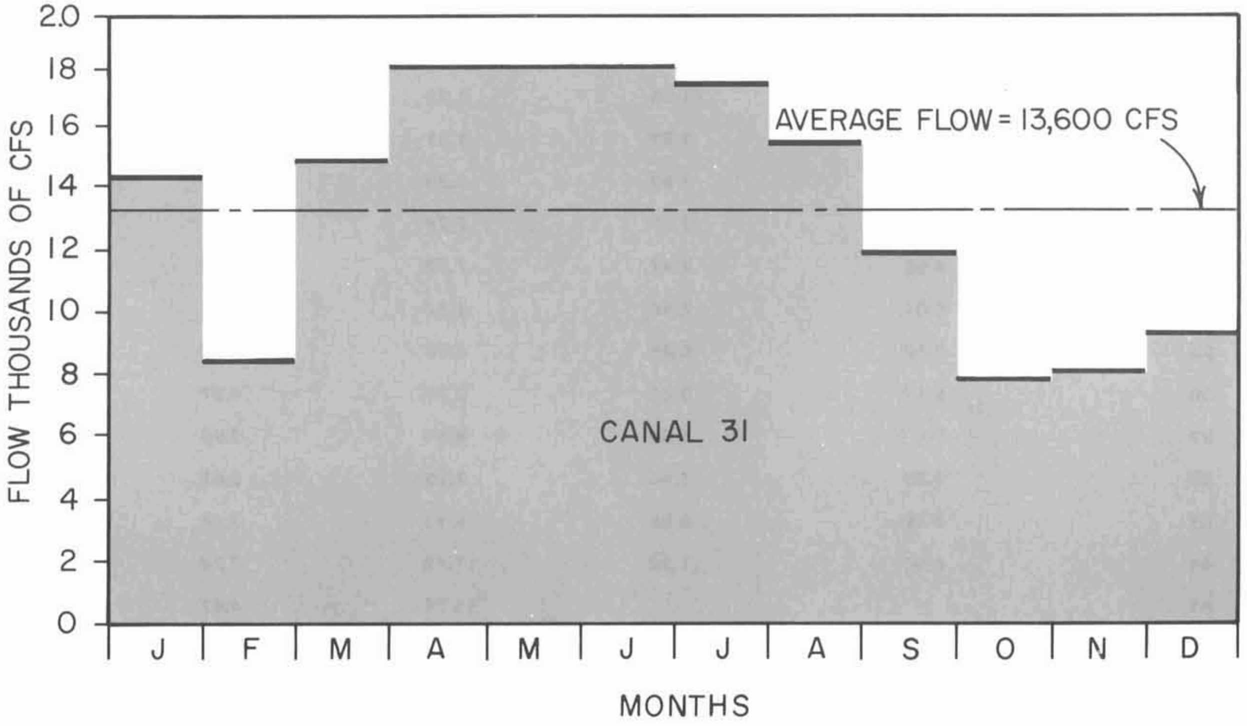


Figure 21

STORAGE CONTENTS OF RESERVOIR 12 AND FLOWS IN LINK 31 FOR YEAR 1 IN THE CANAL SIZING PROBLEM

Table 9.–Summary of Annual Canal Construction and Energy Costs for the Test Problem (millions of dollars per year)

ITEM	UNCONSTRAINED SOLUTION	CONSTRAINED SOLUTIONS			
		NO.1	NO.2	NO.3	NO.4
Canal Construction*	142	122	109	105	102
Energy	86	88	88	88	88

* Based on an interest rate of 4 percent and a repayment period of 50 years.

million acre-feet the reservoir is just filled in April with the canal delivering 18,000 cfs, its capacity. Since flows were variable over the season, it would be expected that a larger reservoir would allow a reduction in size of the supply canal and a saving in marginal costs, both in capital and energy. The marginal cost of the reservoir at this capacity was determined from Texas Water Development Board studies to be about $0.10 per acre-foot per year. The marginal capital cost of the canal was determined to be $0.06 per acre-foot per year, while the marginal cost for energy required to deliver flows to the reservoir was computed from the canal sizing exercise to be about $0.09 per acre-foot per year. Hence, comparing the $0.10 marginal cost of the reservoir and $0.15 marginal cost for the canal plus pumping energy, the choice is clear. The reservoir should be increased in size (if possible) and the canal size decreased.

The element sizing step in Phase I was suspended at four trials beyond the initial unconstrained solution and attention was turned to the development of preliminary operating rules for use in SIM-I and SIM-II.

Phase IB–Reservoir Operating Rules

Both SIM-I and SIM-II require operating rules to predict end-of-month reservoir contents. The form of these rules for the two simulation programs was stipulated in Chapter V as

$$p_{jk} = P_k + f_{jk}\, P_k \quad ;\ 0.0 \leq P_k \leq 0.5,\ k=1,...,12$$

$$p_{jk} = P_k + f_{jk}\, (1\text{-}P_k) \ ;\ 0.5 < P_k \leq 1.0,\ k=1,...,12$$

In preliminary development of these operating rules for the test problems, the Allocation Program was used, functioning under conditions of average hydrology and average demand over the planning period. As in the case of preliminary canal sizing, an assumption was made that final storage levels at the end of the 24-month sequence could be based on an allowable drawdown rate of 20 percent per year from an initial half-full condition. The pattern of rule coefficients which resulted from a solution of this form of the Allocation Problem is illustrated for one of the reservoirs in Figure 22.

From the 24 rule coefficients which were determined for these assumed conditions, 12 were adopted from the middle of the series. These were truncated between the limits of -1 and +1 as shown in Figure 22, wherever values outside these limits had been calculated in the problem. This truncation would have occurred anyway in SIM-I and SIM-II as a necessary condition for the stipulated form of the rules, as given above, and the auxiliary condition that

$$\sum_j f_{jk}\, v_j = 0; \quad j=1,...,n$$

where v_j is the capacity of reservoir j.

Table 11 summarizes the computed seasonal rule coefficients for the 18 reservoirs in the system. Two examples may suffice to illustrate how the adopted rule coefficients for individual reservoirs relate the storage in these elements to that of the system as a whole. The behavior of a reservoir in the region of supply (node 2) is depicted in Figure 23. Figure 24 illustrates the response of a reservoir in the region of demand (node 12).

The supply reservoir is seen to be affected only moderately by the system as a whole, since it is situated at the interior of the system and is buffered somewhat by a reservoir closer to the demand region. However, its accumulated reserve, stored between March and August, is drawn on by the system late in the year as both capacity curves decline together.

The demand reservoir, situated in the High Plains area, is observed to respond in close anticipation of the system capacity curve. Since it is provided with little local inflow, it is filled from lower parts of the system in the early part of the year, drawn on heavily during the irrigation season, and filled during the winter months. As expected, its allowable fluctuations in capacity range widely.

A comparison of rule coefficients in Table 11 with the geographic location of the various reservoirs confirms these general interpretations. Reservoirs close to heavy demand areas, i.e., close to reservoirs 12 and 1, are prime suppliers and are drawn on heavily. Rule coefficients for these tend to be negative, an indication of

Table 10.—Comparisons of Marginal Capital Cost of Canal Construction and Marginal Energy Costs of Capacity Constraints for the Test Problem (dollars per cfs per year)

LINK	MARGINAL CAPITAL COST OF CANAL CONSTRUCTION*	MARGINAL ENERGY COSTS OF CAPACITY CONSTRAINTS, CONSTRAINED SOLUTIONS			
		NO.1	NO.2	NO.3	NO.4
13	120				2,760
14	240				
15	830				
16	120				
17	400	2,760	2,760	2,760	50
18	260				
19	430				
20	140				
21	340				
22	170				
23	610				
24	120				
25	440				
26	490				
27	740				
28	1,020				
29	1,110				
30	700				
31	880			10	10
32	370		50	50	50
33	210		10	630	
34	220				
35	320				630
36	520				
37	960				
38	610				
39	250				20
40	530				
41	490				
42					

* Assuming an interest rate of 4 percent and a repayment period of 50 years.

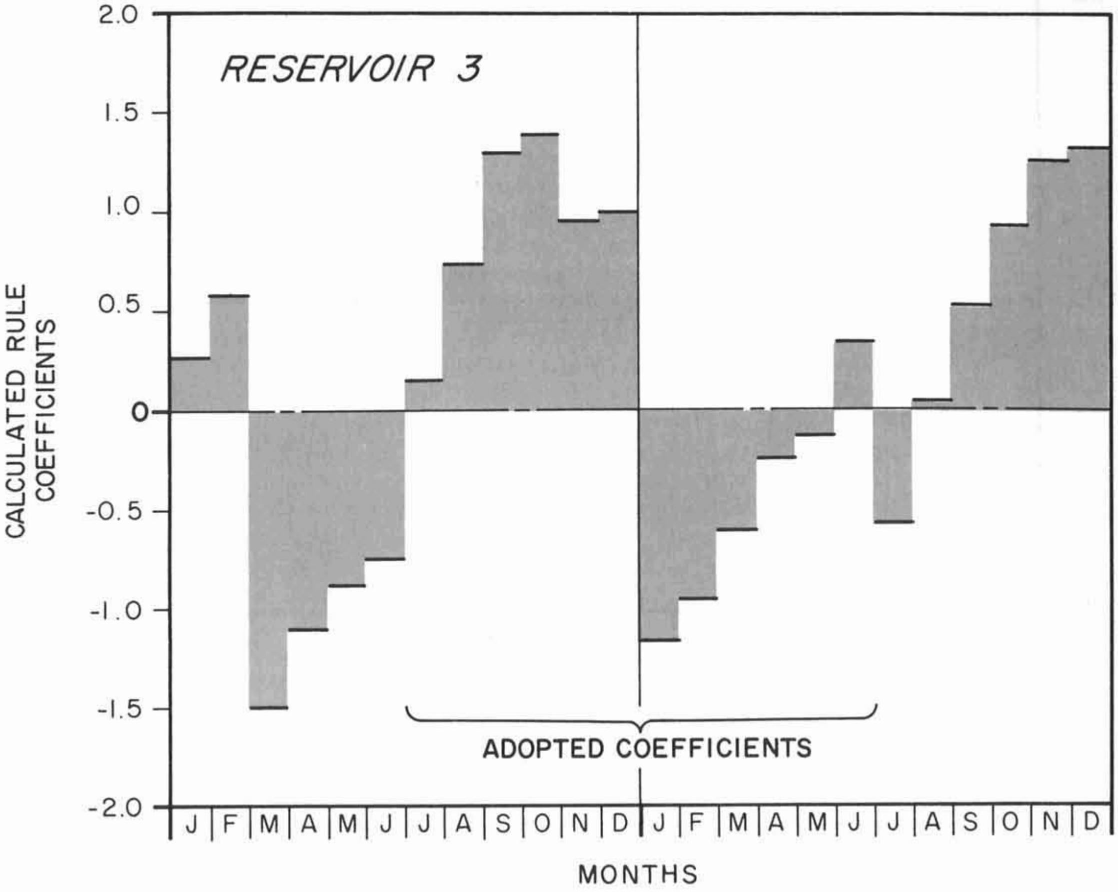
Table 11.—Computed Seasonal Reservoir Rule Coefficients

NODE	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.	AVERAGE
1	-.220	-.335	-.384	-.379	-.768	-.767	-.412	-.055	.035	.081	-.078	-.186	-.289
2	-.196	-.401	-.475	-.037	-.070	-.074	.271	.360	.361	.299	.063	-.058	.004
3	-1.152	-.954	-.599	-.231	-.125	.323	.131	.723	1.309	1.385	.955	1.000	.185
4	.847	1.000	1.000	1.000	1.000	.950	.787	.737	.765	.668	.824	.774	.864
5	-.539	-.470	-.470	-.431	-.784	-.959	-.643	-.259	-.347	-.364	-.416	-.439	-.509
6	-.364	-.481	-.518	-.496	-.877	-.860	-.459	-.151	-.183	-.127	-.222	-.327	-.421
7	-.336	-.699	-1.415	-1.059	1.000	.861	-1.432	-.997	-1.000	-.952	-1.000	-.441	.547
8	.657	.936	1.000	1.000	1.000	.710	.371	.542	.693	.762	.532	.553	.730
9	-.602	-.799	-.836	-.822	-1.197	-.492	-.425	-.200	-.276	-.295	-.395	-.519	-.557
10	-.992	-1.312	-1.224	-1.053	-1.428	-1.707	-1.092	-.893	-1.000	-1.000	-1.000	-1.056	-.992
11	-.711	-.716	-1.415	-1.385	.447	1.000	.651	.234	-.089	-.280	-.476	-.551	-.207
12	.438	.842	1.000	.590	.264	.610	.040	-1.000	-1.000	-.971	-.584	-.076	.013
13	-.915	-.924	-.778	-.748	-.658	-.771	-.868	-.556	-.656	-.782	-.861	-1.033	-.793
14	.995	.443	.928	1.000	.951	.621	.131	.312	.444	.627	1.054	1.000	.704
15	-1.152	.799	-1.415	-.740	1.000	.058	-.325	-.967	-1.000	-.941	-.882	-1.095	-.633
16	-1.152	-1.321	-1.219	-1.385	1.000	1.000	1.000	-.308	-1.000	-.654	1.115	-.848	-.234
17	.559	.559	.555	.161	-.460	-.665	.507	.624	.762	.916	.667	.570	.396
18	.054	.187	.461	.398	.400	.267	688	.539	.436	.222	.045	.021	.310

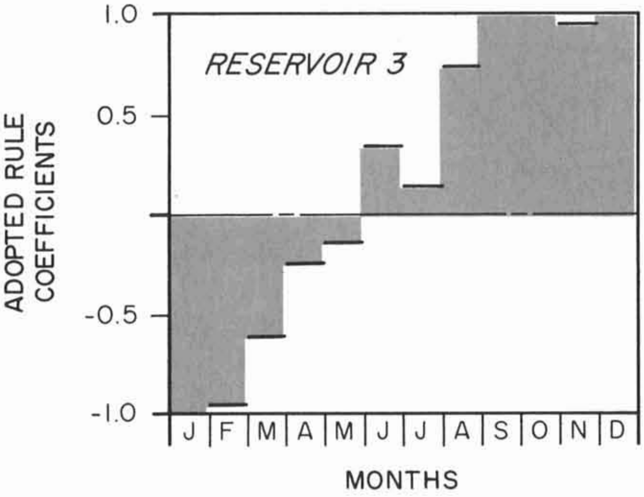
Table 12.—History of Construction Times for 9 Reservoirs and 15 Canals Using the Method of Successive Perturbations

ITERATION	CANALS															RESERVOIRS									PRESENT WORTH OF CREATED RESPONSE (BILLIONS OF DOLLARS)	SHORTAGE (THOUSANDS OF ACRE-FEET)
	13	14	15	16	17	19	22	24	25	27	36	37	38	39	40	1	2	3	4	6	7	9	10	11		
Initial	1	6	4	4	2	4	5	3	6	5	4	5	5	2	5	4	3	3	1	2	5	3	6	6	6.31	33.7
1	7	9	7	7	1	7	8	6	6	2	4	8	8	5	8	4	1	6	7	1	2	1	9	3	6.25	0.0
2	6	9	8	8	1	7	7	6	6	2	4	8	9	4	9	5	3	7	8	1	1	1	10	3	6.18	0.0
3	6	9	10	10	1	7	7	6	6	2	6	8	11	4	11	5	5	9	8	3	1	1	12	3	6.16	0.0
4	6	9	11	11	1	8	7	6	6	3	7	9	12	3	12	6	5	10	9	3	1	2	12	3	6.14	17.9
5	6	10	12	12	1	9	7	6	6	3	8	10	12	3	12	7	4	11	10	3	2	2	12	3	6.10	17.9
6		11	12	12	*	10	*	*	*	3	8	10	12	3	12	8	4	12	11	*	2	2	*	*	6.09	17.9
7		12	12	12	*	11	*	*	*	3	8	11	12	3	12	8	4	12	11	*	2	2	*	*	6.08	17.9
8		12	12	12	*	12	*	*	*	3	8	12	12	3	12	8	4	12	11	*	2	2	*	*	6.07	17.9
9		12	12	12	*	12	*	*	*	3	8	12	12	3	12	8	4	12	11	*	2	2	*	*	6.07	17.9

Asterisk indicates the element is no longer a candidate for staging as construction times stabilized in the first five iterations.



a. CALCULATED COEFFICIENTS



b. ADOPTED COEFFICIENTS

Figure 22

CALCULATED AND ADOPTED RULE COEFFICIENTS FOR RESERVOIR 3

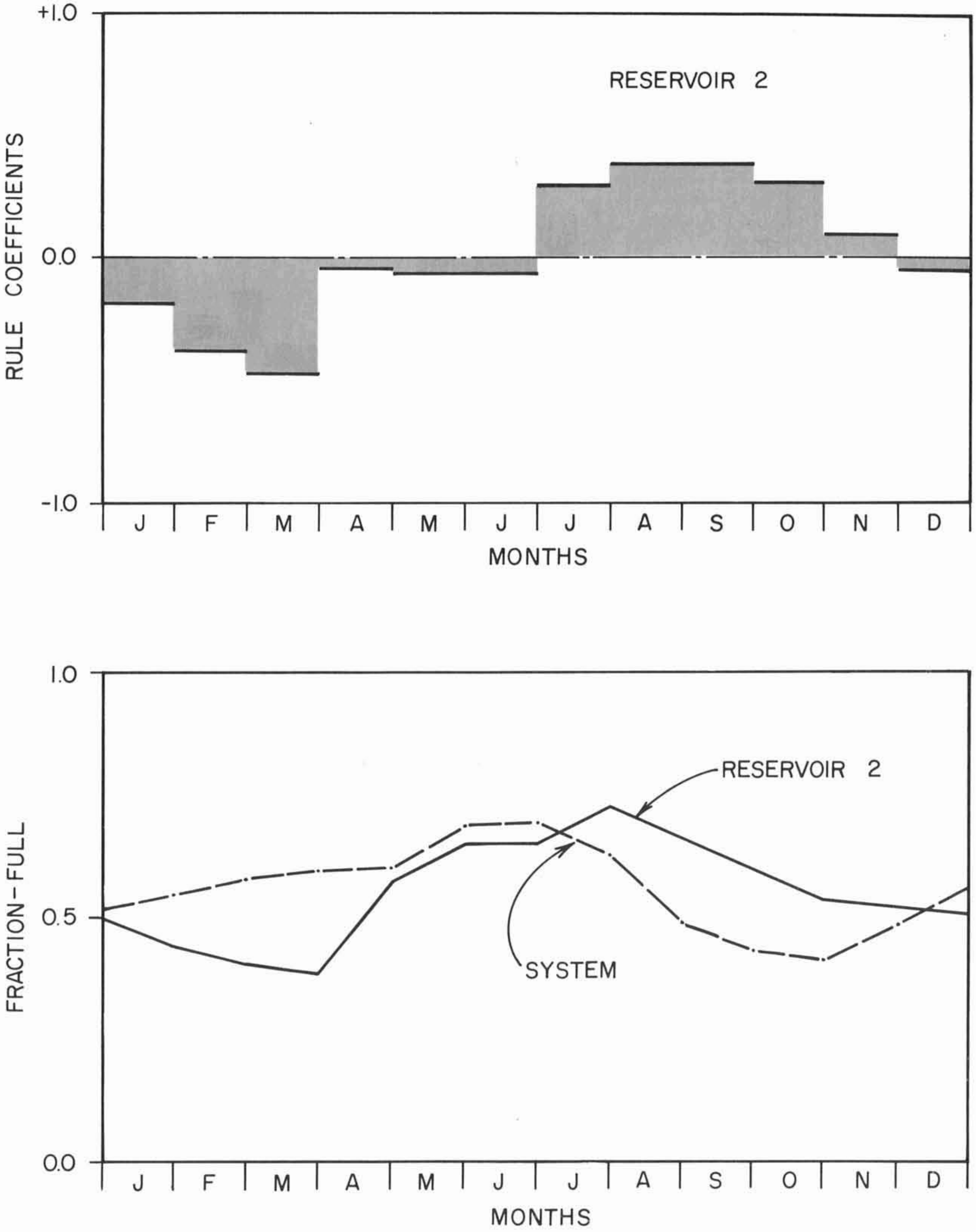


Figure 23

COMPUTED RULE COEFFICIENTS AND FRACTION-FULL FOR A RESERVOIR IN THE REGION OF SUPPLY

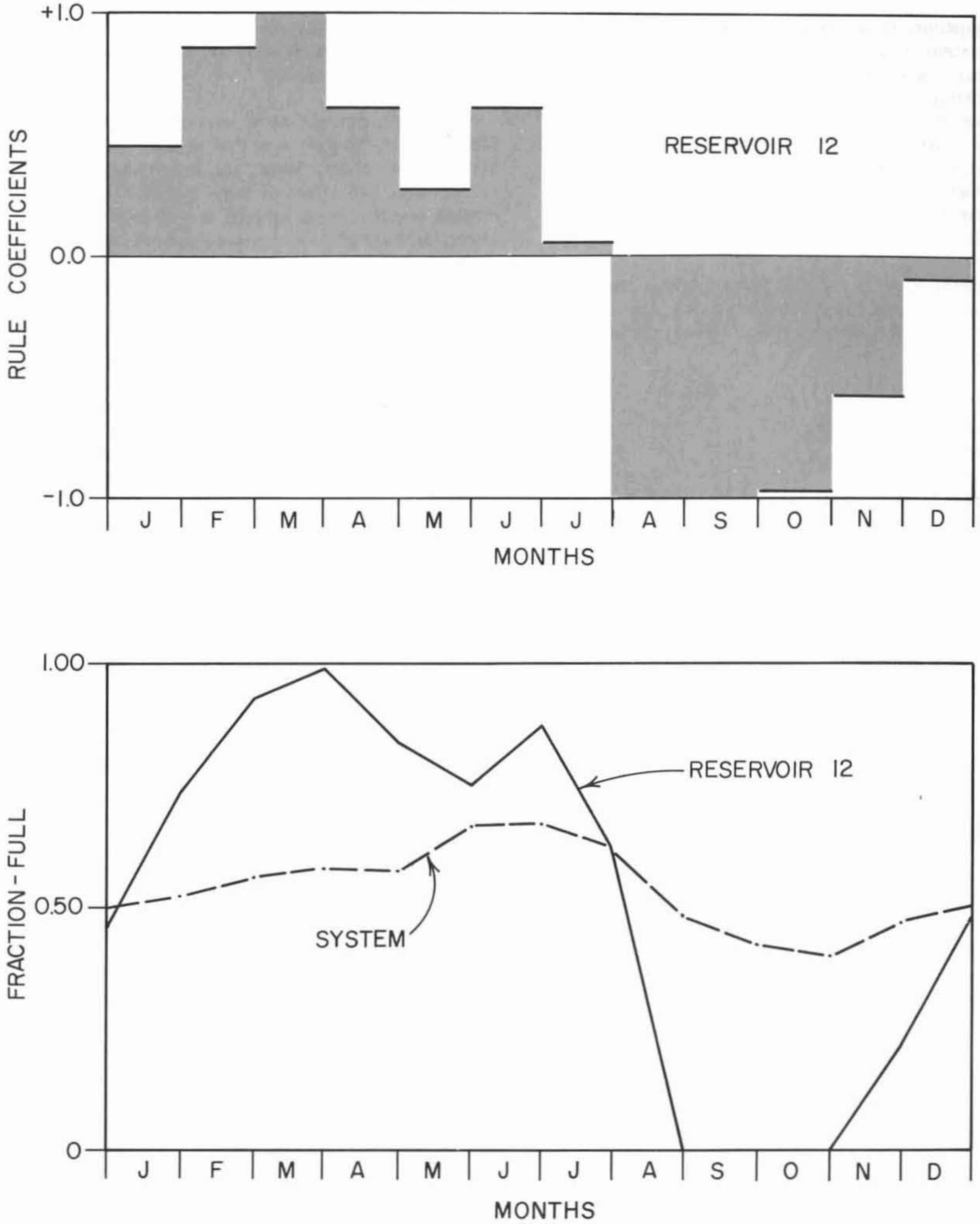


Figure 24

COMPUTED RULE COEFFICIENTS AND FRACTION-FULL FOR A RESERVOIR IN THE REGION OF DEMAND their availability to accept supplies moved up from lower in the system. Reservoirs in remote areas of supply tend somewhat toward positive coefficients, an indication of the tendency to provide reserve supplies, but also a tacit indication that the cost of these waters may be higher than for reservoirs close to demand areas. The import reservoir, it is noted, fluctuates widely in recognition of its assumed role in the system. It is kept full during the period of peak irrigation demand and is usually drawn down at other times.

Operating rules for the test problem, derived in accord with the procedure described above, were utilized in SIM-I and SIM-II in succeeding phases of the planning process.

Phase IIA—Initial Screening, Random Sampling

Phase II of the planning process entails the use of one of two possible initial screening devices, Volume Staging or Random Sampling, followed by the Method of Successive Perturbations to improve the superior alternatives. Evaluations are made through SIM-I using preliminary element sizes and average operating rules from Phase I. The primary objective is to find a "good" development plan, a schedule for development, which can then be submitted for closer evaluation and refinement by SIM-II in Phase III.

For the purposes of the test problem, the initial screening was done with the random sampling technique. Also, since SIM-I was used, the more general structure of the system used in Phase I (See Figure 19) was reduced to the tree-shaped structure shown in Figure 25. Consequently, links 18, 20, 23, 26, 41, and 42 were removed and it was assumed that canal 21 could be placed in service at the same time as canal 22, a condition necessary to prevent looping.

Of the 18 reservoirs in the test problem, 5 already exist and 4 others would have to be available by 1985 to meet demands anticipated in the planning period, 1985 to 2020. The remaining nine reservoirs were subject to staging according to the methods of random sampling and successive perturbations.

Subroutine EXPLOR was utilized to select alternative times after 1985 and before 2020 when the nine reservoirs might be added to the system. One hundred schedules were selected by EXPLOR by a random process, and these were separately evaluated for hydraulic performance and present worth. A created response, CR, was also computed for each alternative schedule based on deficits determined in the simulation and using the penalty function described in Chapter IV.

Figure 26 summarizes the results of the random sampling procedure. Present worth values ranged widely, with a low of $5.92 billion. The distribution was skewed toward the lower value with the mode in the range of $6.3 billion to $6.4 billion.

A basic assumption in development of the Stage Development Program was that deficits should not be permitted to occur; hence, the large penalty for such occurrences. The effect of these penalties was to force created response costs upward and to identify as more attractive those plans which provided greater assurances of meeting demands. By this procedure, the "minimum-cost" plan was one with a created response of $6.31 billion, situated at the lower left corner of the present worth-created response plot of Figure 26. This plan was one which nearly satisfied the stipulated demand over the planning horizon. It actually permitted a small deficit of about 34,000 acre-feet over the planning horizon. According to the plan, as selected by this random process, all of the nine additional reservoirs would have to be built in the first 6 years after 1985.

The normal planning procedure at this point in the process would be to pass a selected number of the most attractive plans on for improvement by the Method of Successive Perturbations, MSP. There is no guarantee that the plan with minimum created response will actually emerge as ultimately superior to all others randomly selected, so it would be prudent to examine others, as well. For practical reasons of time and cost, as well as in keeping with the objectives of the test problem, this procedure was not explicitly followed. Only a single plan, that with the lowest created response, was carried forward for treatment by MSP.

Phase IIB—Initial Screening, Method of Successive Perturbations

The most attractive alternatives derived from applications of EXPLOR or VOLSTG would be expected to lie at points on the response surface which are close to depressions, or optima. The objective of the Method of Successive Perturbations is to force the search toward these optima, the lowest cost alternatives, through an organized adjustment of the schedule for placing system elements in service. MSP begins with a set of scheduled times for each reservoir and canal which must come into service over the planning horizon, successively modifies these times, ahead 1 year and back 1 year, and determines with the aid of SIM-I whether the created response has been improved, i.e., cost has been reduced. The process is continued until the created response can no longer be improved.

The starting point for MSP on the test problem corresponded to the schedule for the best of 100 plans passed through the random sampling process by EXPLOR. That schedule provided for 9 reservoirs and 15 canals to be placed in service in a period of 6 years following 1985 in the sequence identified as "Initial" in

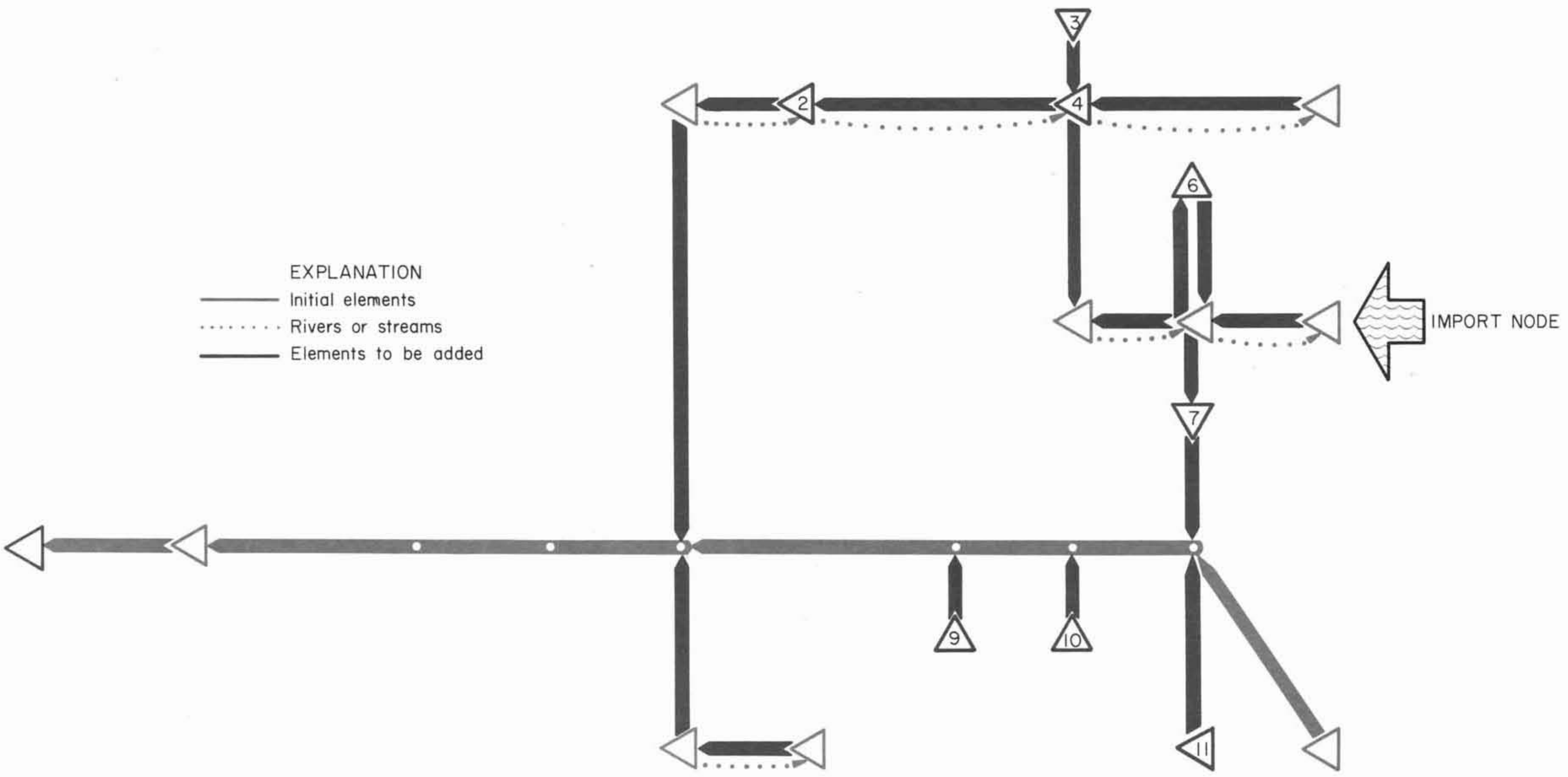


Figure 25

INITIAL AND ULTIMATE SYSTEM CONFIGURATION USED IN PHASE II OF THE DEMONSTRATION PROBLEM

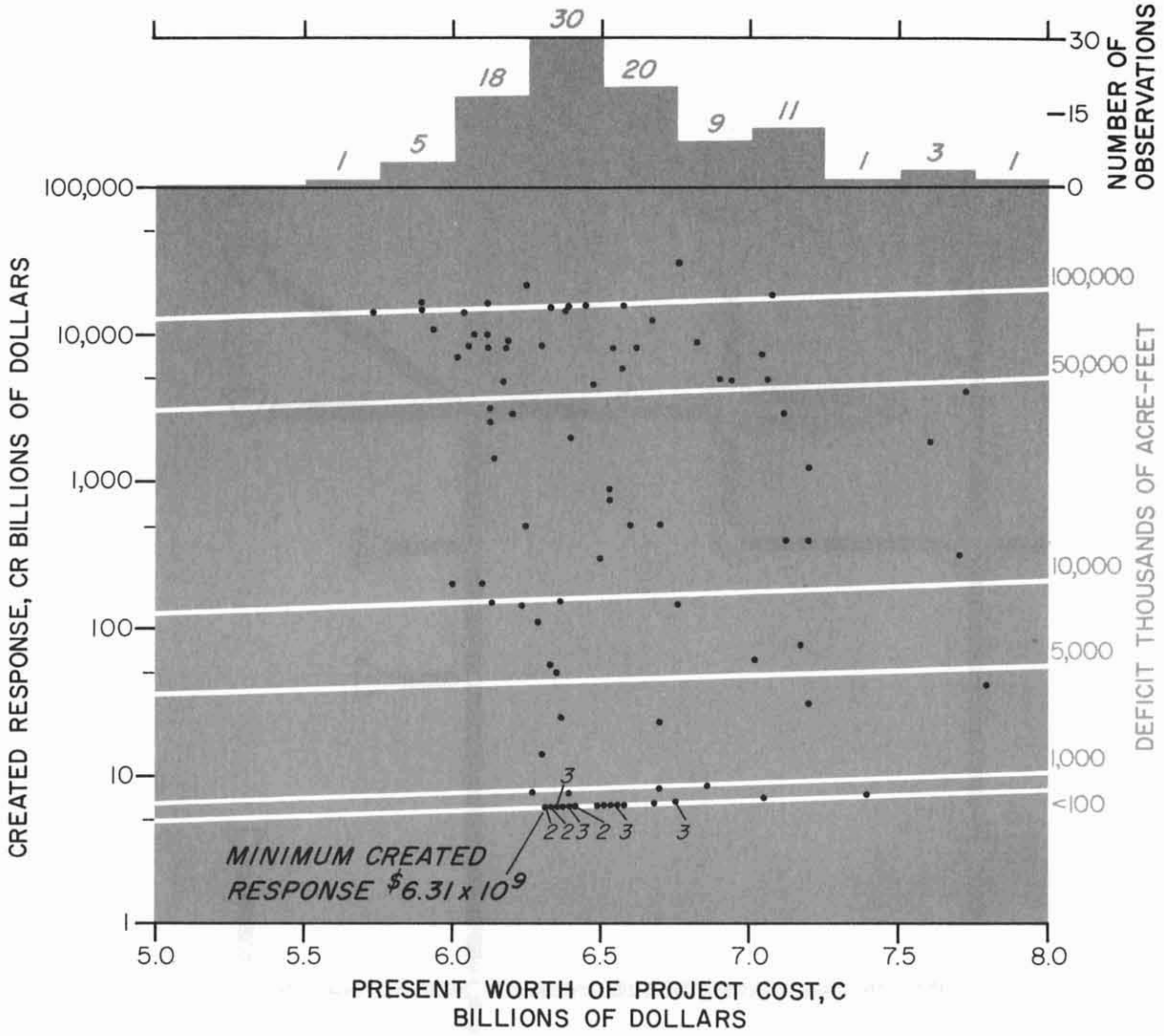


FIGURE 26.—DEFICITS, PRESENT WORTHS, AND CREATED RESPONSES OF 100 RANDOM SAMPLES DRAWN IN THE DEMONSTRATION PROBLEM

Table 12. The initial created response was $6.31 billion and the demand deficit was determined by SIM-I to be about 33,700 acre-feet over the planning period 1985 to 2020.

The first iteration[12] resulted in some marked shifts in the initial schedule, expanding it to cover a period of 9 years, completely removing the deficit condition, and reducing costs by $60 million. The second iteration dropped costs another $70 million and expanded the schedule to 10 years. A third iteration reduced costs by $20 million and expanded the schedule to 12 years; no deficits were associated with this schedule. Thereafter, from the fourth through the eighth iteration, slight improvements were achieved in created response, but the schedule remained 12 years in span and a deficit of 17,900 acre-feet was sustained. A ninth iteration resulted in no change whatsoever in the schedule; hence, no cost improvement. Figure 27 illustrates the reduction in the present worth of project costs during these nine iterations. The schedule resulting from these iterations was regarded as final for Phase II and was passed on to SIM-II where the system's operational characteristics could be more rigorously examined.

A significant finding of this step in testing the planning sequence, aside from confirming the operational

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[12] One perturbation pass through the system plus acceleration in the direction of improved response.

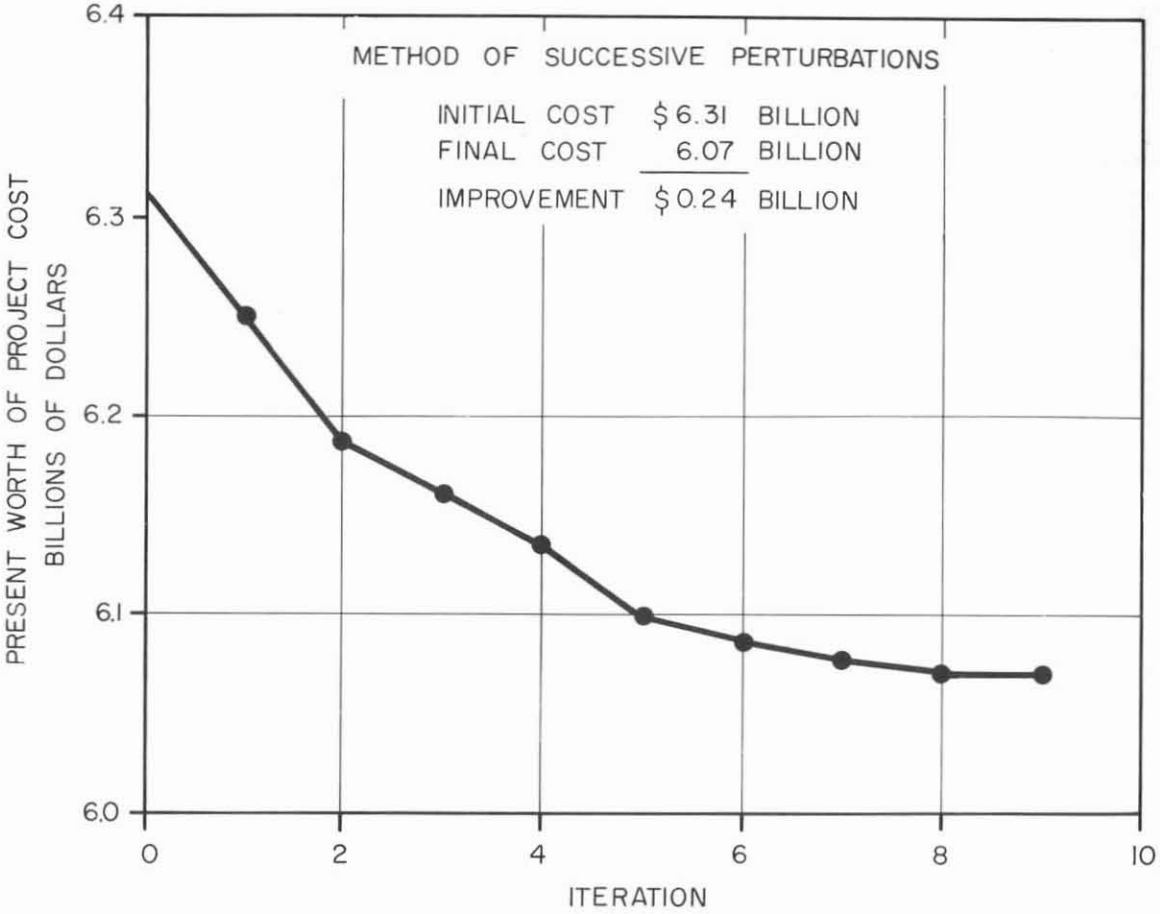

FIGURE 27.—REDUCTIONS IN PROJECT PRESENT WORTH RESULTING FROM THE METHOD OF SUCCESSIVE PERTURBATIONS FOR THE DEMONSTRATION PROBLEM

capability of the technique, was revealed by the flow directions in canals as determined by SIM-I. In canals 35, 36, 37, 38, and 39, serving the most southerly basin of the system (See Figure 19), flows were both positive and negative, that is, imported water had to be *supplied* to this basin. This observation suggests that this basin may not be as well served by the system comtemplated by the test problem as the planner might have hoped.

It must be acknowledged that conclusions based on this sort of simulated behavior, at this stage in the planning sequence, are at best risky and require careful evaluation on the part of the planner. He should reflect on the basic assumptions of SIM-I, the nature of the derived operating rules, and the assumptions concerning demand patterns for the reservoirs in question before taking decisive action to modify the system. It will be seen, however, that this behavioral pattern of the system was confirmed subsequently by both SIM-II and the Allocation Program in the succeeding phases of the test problem. No doubt the system contemplated will be worthy of careful reexamination with all of the advance planning capability which can be made available.

Phase III—Secondary Screening

The objective of Phase III is to find an optimum solution to the system operation problem given certain specifications on system configuration, element sizes, and reservoir operating rules. A schedule for implementation, developed in Phase II, must be provided at the outset; however, it may be adjusted by a trial and error process as indicated by non-feasible solutions to the problem initially posed. SIM-II, which utilizes the Out-of-Kilter Algorithm as an optimization routine, is the basic tool of Phase III.

The test problem, involving 18 reservoirs, 6 non-storage nodes, and 42 canals or river reaches was solved three times for a 36-year period, 1985 to 2020, using the schedule corresponding to Iteration 8 by MSP. (See Table 12). These runs differed primarily in the constraint conditions imposed on the sizes of canals. The first was an unconstrained solution, no limits being imposed. The subsequent runs represented efforts to introduce the subjective decision process into the planning exercise with a view to driving the total cost downward by adjusting selected canal sizes. Table 13 summarizes the results obtained from these runs in terms of canal capacities. Present worth costs for the system are summarized in Table 14.

Table 13.—Canal Capacities Determined by Successive Applications of SIM-II to the Test Problem

(cfs)

CANAL	UNCONSTRAINED	TRIAL 1	TRIAL 2
13	19,024	*14,990*	14,857
14	18,808	*14,990*	*
15	2,473	*299*	*
16	5,013	8,516	*5,993*
17	19,472	*14,990*	*
18	4,781	*2,988*	*
19	1,909	*2,490*	*
20	12,749	13,496	*
21	27,124	25,348	*
22	7,718	8,267	7,586
23	26,543	*9,993*	*
24	16,417	16,517	*
25	27,141	27,141	*
26	16,634	16,318	*
27	16,700	*13,994*	*
28	6,557	7,702	*2,490*
29	24,153	19,488	*
30	24,634	*19,820*	*19,887*
31	24,800	*19,986*	*
32	19,156	*13,994*	*
33	17,646	*13,994*	*
34	18,758	*13,994*	*
35	9,097	*5,993*	*
36	7,686	9,628	7,138
37	5,495	*498*	*
38	2,125	*498*	*
39	10,043	*2,988*	*
40	2,938	*996*	*
41	2,556	*199*	*
42	498	548	*

Asterisk indicates value did not change from previous trial. Italic type indicates flow is at capacity of canal, i.e., constrained.

Table 14.—Present Worth of Alternative Development Plans as Determined by SIM-II

(billions of dollars)

COMPONENT	UNCONSTRAINED	TRIAL 1	TRIAL 2
Reservoirs	0.52	0.52	0.52
Canals	5.21	4.17	4.00
Power	1.14	1.13	1.13
Imports	0.28	0.28	0.28
Total	7.15	6.10	5.93

The unconstrained solution resulted in some unreasonably high flows in certain canal reaches, for example, in sections of the main canal to the High Plains area (Links 29-34). Link 23, connecting the import node and node 6, also was found to require a comparatively high capacity. The total cost for the system, operated with no capacity constraints, was $7.15 billion. It will be noted that this cost is substantially larger than for the "best" plan of Phase II, but also that it corresponds to a more realistic representation of the system's probable true behavior.

In the first trial at constraining flows to specified capacities of selected canals, a marked reduction in cost was achieved, $1.05 billion. The capacities of 20 of the 30 canals were fixed and all of these operated against the constraint at some time during the 36-year planning period. A general result of this exercise was a reduction in average canal flow and the capital and operation and maintenance costs of canals. A slight reduction in energy cost was affected.

In the second trial with SIM-II, three additional canal flows were constrained, those in canals 16, 28, and 36. The result was a futher reduction to $5.93 billion, $170 million less than for Trial 1, and $140 million less than the best plan developed by the Method of Successive Perturbations and SIM-I. Only two of the three newly constrained canals operated at capacity. In the other instance, canal 36, the maximum flow actually dropped and the constraint was not operative.

A necessary condition for SIM-II is the specification of flow direction in canals identified with the system studied. The reader will observe in Figure 19 that flows are indicated from reservoirs 8, 9, 10, 11, 17, and 18 toward the major demand points in the High Plains area. SIM-II, in finding solutions to the test problem as constrained, determined that flows in the links connecting the above reservoirs with the remainder of the system should have been reversed, that is, imported water should have been transferred to these reservoirs to meet the pre-specified local demands or the local demands should have been adjusted, or both. To achieve a solution, the additional imported water required, i.e., the demand deficiency, was actually added to the system and an accounting was made over the 36-year period. For the unconstrained solution, an additional 22 million acre-feet was needed. For Trial 2, about 34 million acre-feet would have to be added to the system to meet the demand pattern for the above reservoirs. These "supplemental" supplies would probably not actually be needed since the system as a whole wasted water over the 36-year period. What is indicated by SIM-II is that provision should be made to *supply water to, as well as export water from the above reservoirs,* i.e., install pump-canals with flow directions such that surplus waters otherwise wasted could be used to meet local demand deficiencies. Such a possibility could be explored with SIM-II in future studies of the system.

Phase IV– Final Screening

Use of the Allocation Program in the final screening of alternative development plans presupposes a fixed schedule of implementation (derived from Phase II, the Method of Successive Perturbations) and fixed sizes of reservoirs and canals which exist or will be placed in the system. Moreover, it is necessary that the plan proposed for evaluation be capable of meeting all demands over the planning period; if not, an infeasible solution will be indicated. Such infeasibility can result from either an improper schedule or incorrect element sizes, or both.

The reader will recall that the schedule developed in Phase II of the test problem allowed a deficit of 17,900 acre-feet to occur; hence, it could be anticipated that an infeasible solution would result from an application of the Allocation Program. What were not so obvious were the reasons for the indicated deficit. To determine these for the test problem, the Allocation Program was run to infeasibility, thus identifying the specific causes and facilitating their correction. It was determined that the deficit was associated with the schedules of Reservoir 9 and Canal 13. Moving schedules for these elements forward 1 year removed the deficit. Although this added slightly to the created response[13/], a deficit-free condition was considered superior. Of course, it was necessary also, for a full application of the program and, consequently, the revised schedule was utilized in the next step.

At this point in the sequence, no guarantees had been provided that the canals or reservoirs had been correctly sized preliminarily in Phases I, II, or III to prevent deficits from occurring. It was necessary to run the Allocation Program to ascertain where canal sizes should be adjusted, and when over the planning period these sizes might become critical, i.e., inadequate to assure satisfying demands. Preparatory to this run, all those canals for which zero flows had been indicated in the initial sizing were set for an unconstrained solution. The capacities of some main canal elements were increased slightly to accommodate some expected increases in demand over the last 2 years of the planning period[14/]. Other canals were constrained at values determined in Phase I or suggested by SIM-II in Phase III.

The Allocation Program was run for a 23-year sequence, 1 year (12 months) at a time, utilizing the 20 percent drawdown criterion applied earlier in Phase I. The program terminated in the 24th year, the last year of an 8-year drought period which had been represented in the deterministic hydrologic sequence. It was determined from this exercise that Reservoir 9 in the lower river basin of the system was emptied and could not comply with the 20 percent per year drawdown criterion. Either this criterion would have to be relaxed or the conditions of import would have to be modified. The reader will recall in this later connection that the earlier applications of SIM-I and SIM-II had also indicated a lack of system capability to import water to this basin.

It would have been possible perhaps to have anticipated the drought's influence on the Allocation Program by spanning greater periods, say 2 or 3 years, in each successive solution. If such had been done, the likely result would have been to draw more heavily on imports or to reallocate water in system storage to carry through the drought. Since the program terminated only in the last year of the eight year sequence of deficient years, it is likely that the solution would have carried through the full 36 years.

It is particularly important to note that the above described behavior of the Allocation Program was more closely related to the *hydrologic conditions* assumed than to the mechanics of program operation and application. This experience further emphasizes the need to determine, in future studies, the sensitivity of the water resource system design to hydrologic as well as other stochastic influences.

Phase IV of the planning process was terminated with the 23-year run described above. Together with a run for the last 2 years, performed earlier, this experience provided most of the essential data for an assessment of the efficiency of the Allocation Program and a confirmation of the logic of the planning sequence. Data for capital costs of canals, $2.90 billion, were directly determinable from this solution, and reservoir costs of $0.52 billion were not modified from those of other test cases. Data for estimation of power costs under the Allocation Program were extended to 36 years by

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[13/] The difference between these two alternatives, if evaluated by SIM-I, would not produce a significant change in the created response, i.e., for practical purposes, both had the same cost, $6.31 billion.

[14/] In Phase I, canal sizes were determined for the next to last year rather than the last year of the planning period, 1985 to 2020.

comparison with data for comparable periods from runs with SIM-I and SIM-II. These costs were estimated to be $1.11 billion. Import water costs were estimated, also by comparison with results of SIM-I and SIM-II, at $0.07 billion. The total cost of the development plan which emerged from Phase IV was estimated to be $4.60 billion, $1.33 billion less than the plan produced in Phase III and $1.47 billion less than that produced in Phase II.

Evaluation of Performance

The effectiveness of the planning techniques presented herein can best be measured in terms of their collective capability to improve on the design of a complex water resource system, i.e., to reduce the cost of construction, operation, maintenance, and purchased water. A good base against which to measure effectiveness would have been a cost estimate for the system prepared without the supposed advantages of these techniques, but no such estimate was available. Instead, the measures must be between the discrete techniques and between their separate capabilities to represent the system realistically and to predict reliably its costs.

In Phases II, III, and IV, cost estimates for various development plans were made with successively more sophisticated programs, SIM-I, SIM-II, and the Allocation Program. Table 15 summarizes the predicted present worth of the "best" plans emerging from each phase and the distribution of costs between the major cost components.

Table 15.—Present Worth of Alternative Development Plans as Computed by SIM-I, and SIM-II, and the Allocation Program

(billions of dollars)

COMPONENT	SIM-I	SIM-II	ALLOCATION PROGRAM
Reservoirs	0.52	0.52	0.52
Canals	4.21	4.00	2.90
Power	1.20	1.13	1.11
Imports	0.14	0.28	0.07
Total	6.07	5.93	4.60

Costs are markedly different for each program, ranging from a high of $6.07 billion for SIM-I to a low of $4.60 billion for the Allocation Program. As expected, SIM-II produced a result between these extremes, $5.93 billion.

It is noteworthy that the largest differences in cost are identified with improvements in the capital cost of canals. Since this is the dominant cost component, attention to improving canal sizing seems to have been well directed. Table 16 summarizes the canal sizing operation through the several phases of the planning sequence, showing the general trend toward more effective use of canal capacity as the system is treated by successively more realistic and sophisticated procedures. Sizes generally declined as the process was carried forward. It is probable that additional attention to canal capacity, perhaps staging of capacity over time, will additionally reduce system costs.

Reservoir costs were held constant throughout the test problem. However, several instances were detected where cost savings might have resulted from modifying reservoir sizes. For example, there exists the prospect for a tradeoff between terminal storage, if it is physically available, and the cost of canals. Also, there is the indicated need for modifying the storage capabilities of reservoirs 8, 9, 10, 11, 17, and 18, either by adjusting operating rules, changing storage availability, or by facilitating importation of new water or that which might other wise be wasted in other parts of the system.

Pumping costs were different between the several plans, largely due to reductions in pumped flows by more effective use of canals. No consideration was given separately to the capital costs for pumping facilities. These should be considered subsequently, particularly as they may be affected by staging to meet variable demands over the planning horizon.

Imported water was most efficiently used by the system as refined with the Allocation Program. This is testimony to the capability of the program to schedule imports when expected and not to allow wastage. It seems unlikely, because the imported water cost is a relatively small part of total cost, that this will figure prominently in future refinements in the technique. Questions concerning the points where imported water should be brought into the system are open for additional study and evaluation.

In concluding this presentation of the results of the test problem, it is appropriate to emphasize once again that the techniques used are not ends in themselves. They must be complemented by the experience of a water resource planner knowledgeable in their use and his judgment must figure prominently in decisions as to how they are to be applied. The programs cannot solve a problem that is not properly stated, nor can they supplant judgment and experience. Used wisely and cautiously—and improved by such use—the planning techniques and programs which have been conceived and implemented in this research can prove to be invaluable aids in the design of complex water resource system.

Table 16.—Canal Capacities Determined by Successive Phases in the Planning Sequence

(cfs)

CANAL	INITIAL	SIM-I	SIM-II	ALLOCATION PROGRAM
13	3,400	15,960	14,857	3,400
14	3,000	15,950	14,990	2,690
15	250	2,120	299	150
16	–	–	5,993	5,710
17	3,600	15,930	14,990	3,600
18	–	–	2,988	3,830
19	–	3,120	2,490	3,730
20	–	–	13,496	5,580
21	–	13,030	25,348	5,580
22	2,240	7,610	7,586	9,840
23	–	–	9,993	12,000
24	7,400	23,490	16,517	12,000
25	12,000	26,130	27,141	12,000
26	12,000	–	16,318	12,000
27	9,000	21,530	13,994	11,000
28	–	5,190	2,490	850
29	17,500	24,860	19,488	850
30	17,860	25,670	19,820	19,850
31	18,000	25,990	19,986	20,000
32	12,000	19,850	13,994	14,000
33	12,000	20,000	13,994	14,000
34	12,000	20,400	13,994	14,000
35	3,000	15,400	5,933	3,000
36	3,540	11,240	7,138	8,960
37	500	5,4710	498	500
38	500	2,120	498	500
39	2,500	13,690	2,388	2,500
40	1,000	4,450	996	1,000
41	500	–	199	200
42	–	–	548	360

(–) indicates the canal was not considered in that phase of analysis

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APPENDIX

PROTOTYPE REPRESENTATION

APPENDIX

PROTOTYPE REPRESENTATION

The physical elements of a surface water resource system were represented as a network of links and nodes. Links fall into two groups, river reaches and pump-canals. River reaches include all those conveyances where water flows by gravity and, therefore, do not incur energy costs for pumping. Pump-canals include those conveyances where water must be pumped, thereby incurring an energy cost. Water transferred in this type of link can be pumped either over a ridge into another river basin or upstream to another reservoir within the same basin.

Nodes also fall into two groups, reservoirs and non-storage junctions. Reservoirs can both transfer and store water, whereas a non-storage junction can only transfer water between links.

Table A-1 contains the symbols used to illustrate a water resource system as a network of nodes and links, and Figure A-1a illustrates a water resource system using these symbols.

Table A-1.—Symbols and Terms Used to Illustrate Water Resource Systems

SYMBOL	PHYSICAL ANALOGUE
	LINKS:
·······→	River Reach (Gravity Flow)
━━━━▶	Pump-Canal (Pumped Flow)
	NODES:
△	Reservoir
━━■━━▶	Non-Storage Junction

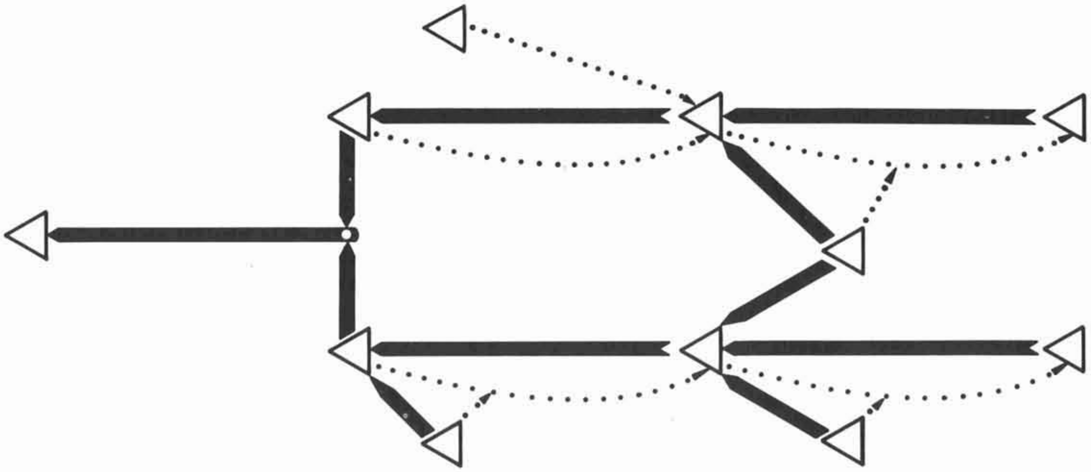
In developing the four computer programs, we subdivided the water resources system in two ways. One classification decomposed the system into *reservoir-canal* and *reservoir-river* subsystems. This classification is based solely on the nature of the connecting links. Figures A-1b and A-1c illustrate these subsystems. For a fully connected system, as shown in Figure A-1a, there is only one reservoir-canal subsystem. If the system is not fully connected, there can be more than one reservoir-canal subsystem. On the other hand, there is always one reservoir-river subsystem for each river basin.

The second classification subdivides the system into a *transfer* subsystem and *gravity* subsystems. The basis for this subdivision is whether or not water can be transferred between reservoirs by a combination of river reaches and pump-canals or solely by river reaches. To visualize the difference between these subsystems, consider the partially developed water resource system depicted in Figure A-2a. Partially developed means that the system is not fully interconnected and that water is not recoverable from all reservoirs.

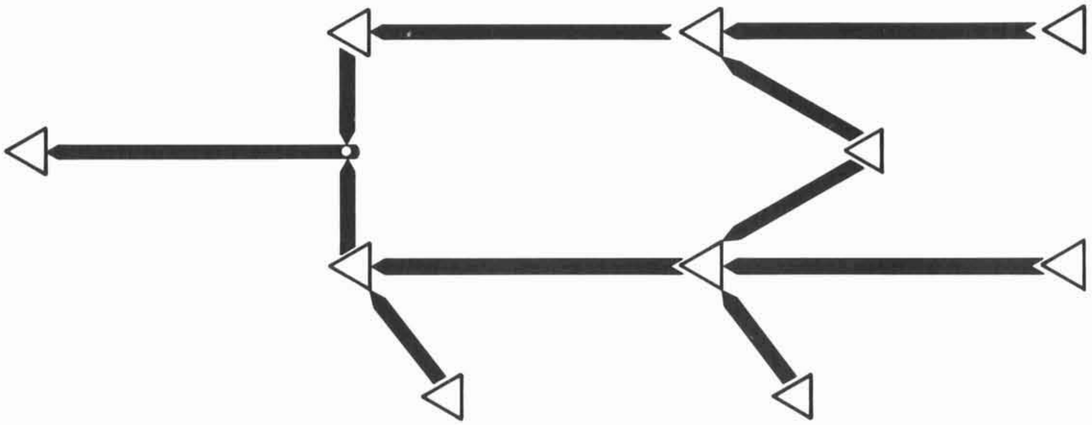
Any water that enters the reservoirs in the gravity subsystem, as illustrated in Figure A-2c, can only be used within that subsystem and is completely "lost" insofar as the rest of the network is concerned. There can be up to one gravity subsystem for each river basin; such a subsystem can represent all or some portion of a river basin. However, when a basin is completely interconnected by pump-canals, it does not have a gravity subsystem. In the example of Figure A-2 there are two river basins but only one gravity subsystem.

If water is in the transfer subsystem, it can be recovered and transferred to another location in the system, either within a basin or into another basin. A reservoir without a canal entering it can be in this classification providing releases from it can be intercepted downstream by another reservoir and transferred upstream by a pump-canal. Figure A-2b illustrates the transfer subsystem of the partially developed system shown in Figure A-2a.

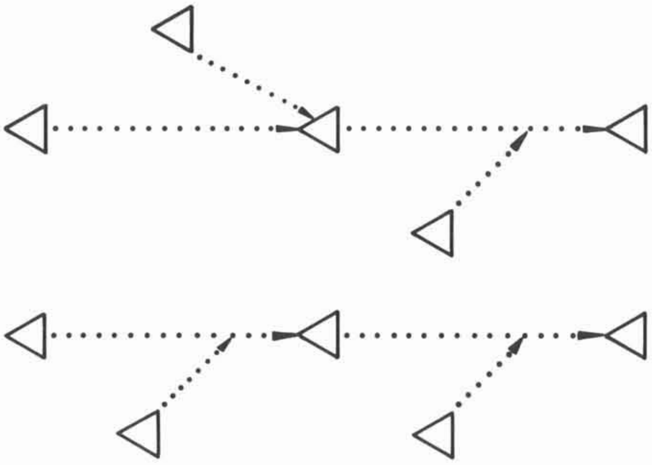
In Chapters IV, V, and VI, which describe the computer programs in detail, we frequently refer to these subdivisions and the terminology used to describe them.



A. FULLY DEVELOPED WATER RESOURCE SYSTEM



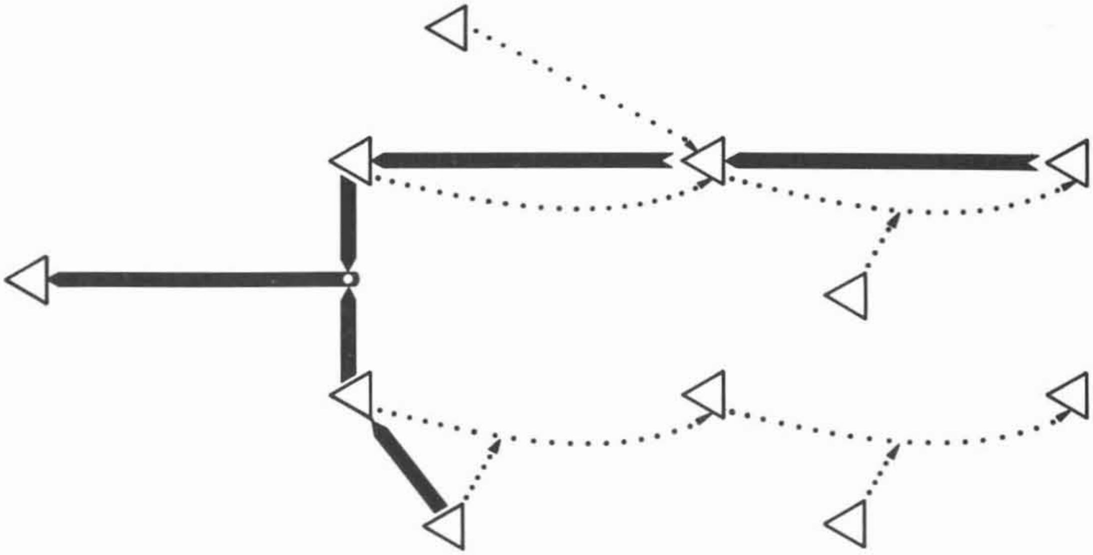
B. RESERVOIR-CANAL SUBSYSTEM



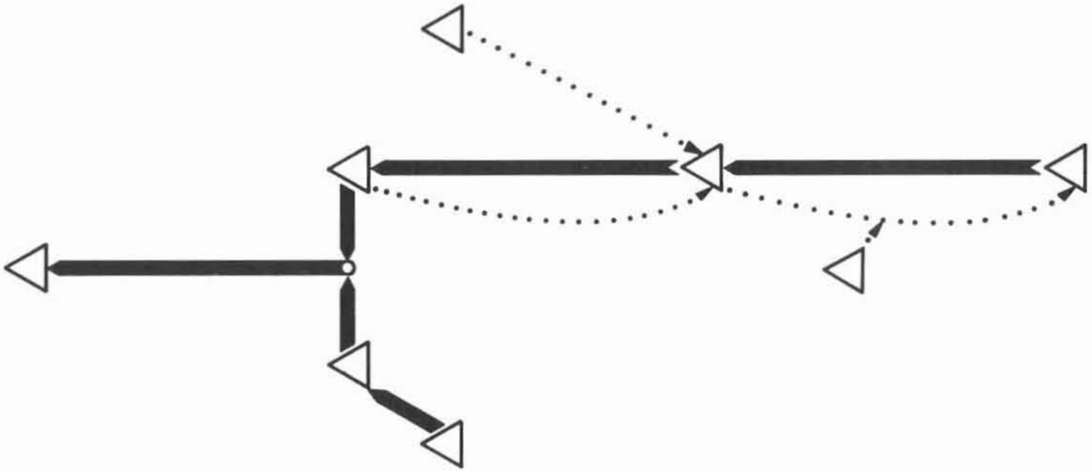
C. RESERVOIR-RIVER SUBSYSTEM

Figure A-1

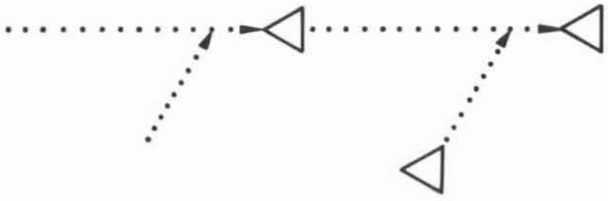
FULLY DEVELOPED WATER RESOURCE SYSTEM DECOMPOSED INTO ITS RESERVOIR-CANAL AND RESERVOIR-RIVER SUBSYSTEMS



A. PARTIALLY DEVELOPED WATER RESOURCE SYSTEM



B. TRANSFER SUBSYSTEM



C. GRAVITY SUBSYSTEM

Figure A-2

PARTIALLY DEVELOPED WATER RESOURCE SYSTEM
DECOMPOSED INTO ITS TRANSFER AND
GRAVITY SUBSYSTEMS