A MULTIOBJECTIVE APPROACH TO THE RESERVOIR OPERATION PROBLEM WITH STOCHASTIC INFLOWS

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PREFACE

This study is concerned with the reservoir operation problem. The problem involves finding appropriate release decisions from existing reservoir systems. Generally, water is released from reservoirs in order to serve several purposes such as municipal and industrial (M&I) water supply, downstream low flow augmentation, flood control, hydroelectric power generation, recreation, etc. Some of these purposes are usually conflicting and there is no single solution which can simultaneously satisfy all of them. Thus, a compromise solution which depends highly on the reservoir manager's judgement is usually adopted.

A mathematical model for the problem is developed in this study. The model considers the three important characteristics of the problem which are: multiple objectives, stochastic inflows, and large-scale systems. One period correlation of inflows in successive periods is assumed to be significant. Conditional distribution functions based on normal and lognormal distributions of inflows are provided. The model is designed to be applicable to any type of system configurations. The solution procedures for the proposed model is based on the chance-constrained goal programming (CCGP) methodology. A computer program for the CCGP methodology is provided. It is designed to be interactive so that the decision can be modified from one iteration to the next until a satisfactory solution is obtained. The methodology is applied to a real world system which is a portion of the Red River reservoir system in Oklahoma.

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CHAPTER I

INTRODUCTION

The General Problem

Water has long been recognized as an essential part of human life. It is used for human consumption and sanitation, for the production of many industrial goods, and for the production of food and fiber. It is a means of transportation in many parts of the world and a significant factor in recreation. The availability of water varies greatly with place and time. Too much or too little water at a place during a long period of time will frequently cause a major disaster to that region. Since ancient times, mankind has tried to avoid these disasters by constructing systems to control water for useful purposes. Today, with world population growing rapidly, the water resources of the world are becoming scarce. It is important that they be used and controlled in the most effective way for the benefit of the largest number of people.

One of the most popular and effective ways to control water in a particular region is to construct a system of reservoirs along the rivers of that region. Decisions pertaining to levels of water stored in reservoirs and the amount of water released from them can be made in accordance with various purposes which are present during a specific time period. For example, in a situation where a flood is likely to occur, the water levels in reservoirs should be low so that they can absorb incoming water. For the same reason, releases from reservoirs should be made carefully during a dry period so that there will be water left for later periods. Reservoirs are constructed to control water for several purposes such as flood protection, drought protection, recreation, hydroelectric power generation, navigation, water supply for municipal and industrial uses, downstream low flow augmentation, and irrigation. It is a difficult task to determine appropriate operating policies for a reservoir system which serves several purposes since some of them are conflicting and noncommensurate. This is a problem which has been studied by many researchers and is known as the "reservoir operation problem".

In earlier days, the determination of reservoir operating rules was based heavily on the judgements of reservoir managers. Typically, a manager would observe inflows and levels of water stored in various reservoirs at the beginning of a time period, and would then specify the amount of water which was to be released from the reservoirs during the time period. So-called "rule curves" based on several years of a manager's experience can be established to provide guidelines for scheduled releases. This approach, although simple, tends to be unreliable, myopic, and uneconomical. There are indications that significant improvements can be achieved by means of optimization techniques which often lead to more comprehensive planning and operation procedures. The annual benefits derived from such improved methodology may easily amount to several million dollars (Tennessee Valley Authority (TVA), 1974).

During the past two decades, many researchers have applied the concept of system analysis to the reservoir operation problem. Various mathematical models of the problem have been formulated and solved by different optimization methodologies. Read and Rosenthal (1982) indicated that there are three major benefits resulting from the system analysis approach.

1) The approach provides solutions which, in many reservoir systems, lead to improved operating policies. Substantial increases in savings are often achieved for relatively small improvements in operating efficiency.

2) The approach may be used to check the decisions made by the reservoir manager. In this way, the manager often gains insight into the nature of the problem and becomes more confident in the final decisions he makes.

3) The approach may be used in studies of alternative system configuration. New systems can be investigated without being actually built. This provides valuable information for future planning.

Statement of the Problem

A typical water resource system is characterized by an integrated operation of multiple reservoirs and related facilities for multiple objectives. These objectives include flood protection, drought protection, recreation, hydroelectric power generation, navigation, water supply for municipal and industrial uses, downstream low flow augmentation, and irrigation. As a result, to satisfy all purposes, decisions about periodic water releases are often difficult to determine due to the large scale, multiobjective nature, and nondeterministic inflows of the system.

Over a period of twenty years, a great deal of attention has been paid to the reservoir operation problem. Several optimization methodologies have been developed in order to find optimal operating policies for various systems. Due to problem complexities, it is not possible to incorporate all the characteristics of the problem into any one model. Typically, in developing a model, trade-offs have to be made between simplicity and reality. The models developed so far range from simple to very complex. A general observation made by researchers in this area is that models which are too simplified normally do not realistically represent real world systems and often produce meaningless output while very complex models tend to be computationally unattractive, difficult to understand, data dependent, and highly system specific. Thus, any model which belongs to either one of the two extremes is not likely to be accepted by practitioners.

There are several factors which characterize the mathematical models of the problem. Some of the important ones usually considered are:

1) System - single or multiple reservoirs
2) Planning horizon - long term, mid term, or short term
3) Functions - linear or nonlinear
4) Inflows - deterministic or stochastic
5) Objective - single or multiple

A particular combination of these factors has to be identified by the modeller. For example, a model may be developed to solve a two-reservoir system over a period of one year, the objective function and all constraints are linear, inflows are treated as deterministic, and the primary purpose is for flood protection. While some of the above factors depend on the system configuration and availability of data, the other factors depend on the viewpoints of modellers. These different viewpoints among researchers in this area have been recognized as the major controversies of the reservoir operation problem. Each of the factors is addressed next.

Although there exist some single-reservoir systems, a resevoir system is normally considered as several connecting reservoirs jointly operated. An optimization routine which can effectively handle multiple-reservoir systems can also be used in single-reservoir systems, but not vice versa. There are several research efforts which have been primarily directed toward single-reservoir systems and many of them become highly inefficient when applied to multiple-reservoir systems. One of the most active areas in the reservoir operation literature is the development of methodologies which can be used in large-scale systems.

With respect to the planning horizon, reservoir models may be divided into three classes which are long-term, mid-term, and short-term models. Long-term and mid-term models are used for planning purposes in which decisions pertaining to scheduled releases may be given monthly and weekly, respectively, for a period of one year. Short-term models are often referred to as "real-time" models since the decisions obtained from the model are used for actual operations rather than for planning purposes. The time steps used in the models are much shorter such as hourly or daily, and the operating horizons of the models may be a week or less. While most of the earlier models are planning models, recent attention has been shifted to real-time models. There are no major differences in the types of optimization techniques used in planning and real-time models since most of the techniques may be applied to both of them. However, some general guidelines for real-time models are such that the computational requirements of the models should be small since they are used for actual operations and decisions have to be made relatively quickly, perfect forecasts are usually assumed, and objective functions should be simple and reflect short-term goals.

Objective functions and constraints in reservoir models can be linear or nonlinear depending on the purposes and configurations of the systems. For example, reservoirs which are used for hydroelectric power generation usually have corresponding nonlinear models. When nonlinearities are present, considerable computational time is expected. Generally, there are two ways to deal with this problem: solve the models with any appropriate optimization routines that can handle nonlinearity or linearize the nonlinear functions so that linear programming can be used.

Literature in this area varies widely according to the assumption about the nature of inflows. While stochastic inflows assumption is more realistic, a considerable large amount of work has been directed to the deterministic inflows assumption. The motivation for the second assumption is due to computational difficulty of the first one. Yakowitz (1982) indicated that there are two viewpoints forwarded in the literature to support the deterministic inflows assumption. One viewpoint is that some rivers are regular enough that their flows are well represented by their expectations. The other viewpoint is that insight is to be gained by retrospectively seeing what the optimum policy would have been if the inflows were known. However, Yazicigil and Houck (1984), among others, pointed out that there are two significant drawbacks of the deterministic models. One drawback is that they do not provide general operating rules because all operation of the system is related to the specific sequence of inflows. The other drawback is that perfect forecasts are assumed which can lead to very optimistic results. The assumption about inflows has been debated in the past, and is likely to remain debatable for a long time. Among researchers in the deterministic inflows direction, there are two popular approaches. One is to use only one set of representative inflows. The other is to use a sequence of sets of inflows and to regress on the decisions obtained from the various sets in order to provide general operating policies. Two approaches are also employed in the stochastic inflows literature in which inflows are either assumed to be independent or correlated. Due to the computational difficulties, work in the correlated inflows direction has gone only as far as one period correlation, i.e. the current inflow depends only on the last period inflow. The "lag-one" assumption is known in the stochastic processes literature as the Markov assumption.

Although reservoir systems are generally operated to serve several purposes, most of the optimization models developed earlier are primarily designed for a single purpose. Typical approaches are either treating one objective as the primary objective with the others as constraints, or somehow making all objectives commensurable and optimizing with respect to the "economic-efficiency" aspects. No attempts were made to determine trade-offs among various objectives in these models. However, recent attention has been directed toward the multiple-objective approach. There are several reasons for the need of multiple-objective models:

1) For public systems such as the reservoir system, it may not

be appropriate to base decisions only on the "economic-efficiency" viewpoint.

2) Several objectives are usually noncommensurate and it is difficult to assign the same utility measure to all of them. For example, one may wish to estimate flood control benefits strictly in terms of lives saved and energy benefits strictly in the amount produced.

3) It is extremely difficult and unsuitable to assign dollar values to some objectives such as flood control, drought control, and recreation.

4) By assigning the status of a constraint to an objective, the relative importance of the objective to others may be improperly fixed.

5) Societies and government agencies are placing increasing importance on several nonmonetary objectives such as recreation and water quality. In fact, water resource problems are among the few problems which have been officially recognized by the United States government to be multiobjective in nature (Cohon, 1978).

Traditionally, an objective function corresponding to a particular purpose of either single or multiple-objective models is to be maximized or minimized. For example, it may be required to maximize the amount of hydroelectric power, maximize the number of recreational visits to the reservoir, or minimize the losses due to flood, etc. A major difficulty of this approach is the unavailability of data which is typical of many of the reported studies. Thus, the data required to form appropriate objective functions of the model are usually approximated or collected over a period of time. Consequently, this traditional approach has suffered from several drawbacks such as model inaccuracy due to poor approximations, large amount of time needed to spend in data collection, and tendency of the model to be highly system specific. This difficulty with the objective function seems to be the major motivation for most of the earlier studies to consider only single-objective models since multiple-objective models were likely to make the problem even more complicated. In contrast to the traditional approach, several researchers such as Houck (1982), Can and Houck (1984), Chisman and Rippy (1977), and Datta and Burges (1984) have employed the ideas of "penalty function" which takes advantage of the information readily available in most reservoir systems. Generally, the target amount of releases and storage levels for various purposes are set from contract requirements, legislation, or other means such as contracted amount of water for industrial uses, municipal water demand, and contracted amount of hydroelectric power. Thus, the objective function may be based on this "penalty function" in which penalties are assigned to any deviations from the respective targets of various purposes.

In spite of a large amount of work done in the reservoir operation area, little attention has been directed toward the development of a model which combines the three important characteristics of the problem together. These three characteristics are multiple reservoirs, multiple objectives, and stochastic inflows. A meaningful and practical model should be able to handle the problem with these characteristics within reasonable computational requirements. Due to conflicting natures of some objectives in the model, it is usually difficult to identify the compromise solution which is acceptable for all objectives. Consequently, with the noninteractive approach commonly employed by most of the existing models, the reservoir manager may need to solve the problem several times before he can obtain a satisfactory solution. An interactive model which allows the reservoir manager to participate during the problem solving session instead of before or after would be a more appropriate approach. With this approach, he can progressively provide his decision pertaining to target values as well as his preference information for various objectives, and modify his decision from one iteration to the next, if desirable, until a satisfactory solution is reached.

The development of an interactive model with the three characteristics mentioned above is the major objective of this research.

Research Objectives

This research has two sets of objectives: the primary objectives and the secondary objectives. The primary objectives focus on the development of a suitable model for the reservoir operation problem and on the determination of an appropriate solution algorithm. The secondary objectives are to develop a computer program based on the solution procedures and to demonstrate the applicability and suitability of the proposed model by applying it to a real world system. In addition, a sensitivity analysis involving some parameters in the model will be performed. The primary and secondary objectives of the research can be stated more explicitly as follows:

Primary Objectives

1) To develop a mathematical model for the reservoir operation problem. The model will be designed to reflect the following characteristics of the problem:

a) Multiple objectives which are normally conflicting and noncommensurate. Various objectives to be considered are:

- flood protection
- drought protection
- water supply for municipal and industrial (M&I) uses
- hydroelectric power generation
- recreation
- downstream water supply for requirements such as water quality enhancement, navigation, low flow augmentation, and irrigation.

b) Stochastic inflows with correlations between them explicitly considered

c) Multiple-reservoir systems

2) To develop an apropriate solution algorithm for the model.

Secondary Objectives

1) To develop a computer program based on the algorithm determined above. The program is designed to be an interactive routine so that the reservoir manager can iteratively provide his decision pertaining to various target levels and preference information about various objectives.

2) To demonstrate the applicability and suitability of the model by applying it to a real multiple-reservoir system.

3) To carry out a sensitivity analysis involving some parameters in the model.

The model developed in this research is designed to aid the reservoir manager in making decisions. Following are some desirable characteristics of the model:

1) It should be realistic enough so that the results obtained are meaningful.

2) It should also be simple enough so that actual implementation is possible.

3) The computational requirements should be reasonable

4) It can be applied to more general systems rather than a specific one.

Outline of Contents

In this chapter, the general overview and statement of the research problem have been presented. In addition, the objectives of the research have been outlined. In Chapter II, a literature review of work involving the reservoir operation problem will be presented. Decision making with multiple objectives is the topic of Chapter III. An overview and classification of various multiple-objective methodologies will be provided. A brief description of one methodology known as "goal programming (GP)" together with its extensions will be presented. In Chapter IV, a mathematical model which explicitly considers the three characteristics (i.e. multiple objectives, multiple reservoirs, and stochastic inflows) of the reservoir operation problem will be developed. A solution methodology based on goal programming referred to as "chance-constrained goal programming (CCGP)" will be described. Chapter V is the application of the proposed methodology to a real reservoir system. Chapter VI provides the conclusions and identifies some possible extensions of this research. The description of the interactive computer program and the program listing are included in Appendixes A and B, respectively. Finally, pertinent data of the reservoir system considered in Chapter V are included in Appendix C.

CHAPTER II

BACKGROUND OF THE RESEARCH

Introduction

The reservoir operation problem is one of the most popular topics in the water resource literature. The application of system analysis methodologies in which various optimization models are employed to determine the optimal operating policies has enjoyed a great deal of attention during the past two decades. Numerous studies have been reported in several books such as Hall and Dracup (1970), Haimes et al. (1975), Cohon (1978), Major and Lenton (1978), Loucks et al. (1981), in survey papers such as Read and Rosenthal (1982) and Yakowitz (1982), and in several hundred articles. Due to the large amount of studies, it is not possible to address each of them individually. This literature review will group various representative studies into three major categories in order to provide some idea about the past, present, and future trends of the studies. Within each category, the studies will be further categorized by the types of optimization methodologies used. The three major categories of the studies in this area in decreasing order of the amount of work done are:

1) Systems with single objective and deterministic inflows
2) Systems with single objective and stochastic inflows

3) Systems with multiple objectives and deterministic inflows.

In single-objective models, optimization is performed with respect to only one objective. One typical approach is to consider the primary purpose as the objective function and the other purposes as constraints. For example, the objective of a model may be to maximize the amount of hydroelectric power, and the constraints of the model are related to other purposes such as water supply for municipal and industrial uses, storage level for recreation, water supply for irrigation, etc. Another typical approach is to assign the same utility measure, such as dollar values, to all purposes and optimize with respect to the "economic-efficiency" aspects in which either benefits are maximized or costs are minimized. In these single-objective models, there is no attempt to perform trade-offs among various purposes. Systems are considered to be deterministic if inflows, either a set or a sequence of sets, are assumed to be known with certainty. Forecasting routines are normally used to identify the future inflows.

It is felt that dividing the vast amount of studies this way will provide a clear perception of the work done and identify the needed further work, although the literature in this area may be categorized in terms of other factors such as number of reservoirs in the system, planning horizon, nature of functions presented in the model, or type of objectives considered.

Reservoir Characteristics and Basic Model

As a reference for various optimization models to be reviewed next, a schematic representation of a reservoir, description of its various storage zones, and a typical formulation of a very simple single reservoir system are provided.

Figure 1 shows various zones of a multipurpose reservoir. In general, there are three primary storage zones, any or all of which may exist in a given reservoir project. These three primary zones are flood control, conservation, and inactive storages. In some cases, these primary zones are subdivided further into smaller zones. Each of the primary storage zones is discussed next.

The flood control storage is the uppermost storage space in the reservoir. During high runoff periods, the reservoir level will rise into the flood control pool. During these periods, flood control storage is used so that downstream channel capacity will not be exceeded. When water is in the flood control pool, maximum allowable release should be made in order to empty the flood control pool. In some cases this storage has been subdivided into two, one immediately above the conservation storage and the other on top of the first. The latter is called spill or surcharged zone (Sigvaldason, 1976).

The conservation storage is the storage zone immediately below the flood control storage. It is the zone where the reservoir will operate most of the time. It may be used to regulate minor floods as well as supply water for various conservation purposes such as navigation, hydropower, recreation, irrigation, etc. For this reason, a seasonally varying boundary between flood control storage and conservation storage (instead of a straight line as shown in Figure 1) is often advantageous to both flood control and conservation. If several conservation purposes of different priorities exist, the conservation storage may be further subdivided into a buffer zone and one or more storage zones

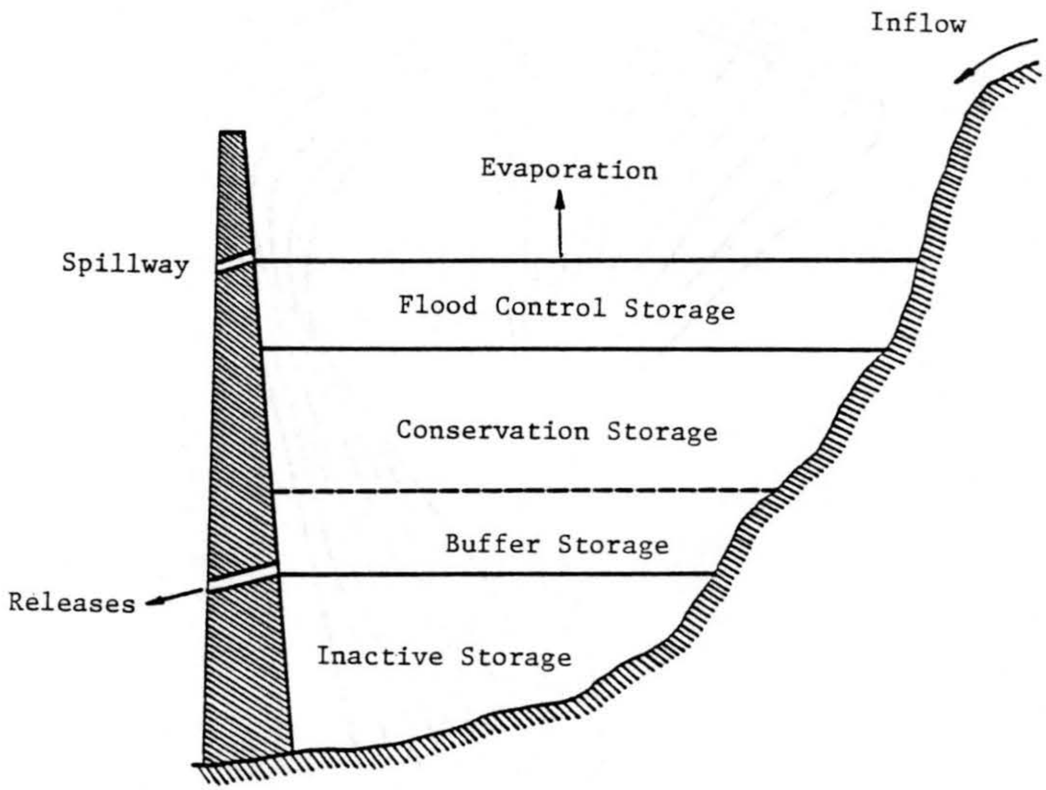

Figure 1. Reservoir Storage Zones

above the buffer storage. The buffer storage can be thought of as a lower emergency zone where storage is becoming critically small and only the most essential water demands (i.e. high priority demands) are met. Within this zone, releases are minimized in order to conserve available water. Above the buffer storage there may be one to five conservation storages depending on the level of flexibility required by the system. The boundaries among these zones are normally specified based on the judgement of the reservoir manager.

The inactive storage is the storage at the bottom of the reservoir. It is the storage which is maintained in the reservoir for various purposes, e.g. maintenance of a recreational pool, maintenance of head for power, maintenance of reserve for sedimentation. As a rule, the reservoir may not be drawn below the top of the inactive storage. However, the top of the zone may be allowed to vary seasonally in some instances. For example, if the inactive storage is provided only to maintain a recreational pool, it might be permissible to withdraw water from the inactive storage for other conservation purposes during the season when there is little or no use of the reservoir for recreation.

For a typical reservoir, there are certain requirements which must be satisfied at all time. First, the storage level must not exceed the capacity of the reservoir. Second, the storage level must not be below the minimum allowable level. And third, the so-called "continuity equation" which links the storage level, the inflow into the reservoir, and the release from the reservoir, must hold during any time period. These requirements can be expressed mathematically as follows:

1) Continuity equation

$$S_t = S_{t-1} + I_t - R_t \qquad t = 1,2,\ldots,T \qquad (2.1)$$

2) Maximum allowable storage level

$$S_t \leq S_{max} \qquad t = 1,2,\ldots,T \qquad (2.2)$$

3) Minimum allowable storage level

$$S_t \geq S_{min} \qquad t = 1,2,\ldots,T \qquad (2.3)$$

where

S_t = storage in the reservoir at the end of period t.

R_t = amount of release in period t.

I_t = inflow in period t.

S_{max} = maximum allowable storage.

S_{min} = minimum allowable storage.

T = number of periods in the model.

These are typical constraints which must be satisfied by the system. In addition, there are many more constraints and goals to be considered in real systems which make the problem much more complex. The other constraints not included here reflect the relationships among various reservoirs in the system, reflect the requirements from various purposes, and reflect other physical characteristics of the system.

Systems with Single Objective and Deterministic Inflows

Research in this direction has been very active even at the present time. Studies in this section may be classified according to the optimization methodologies used, which are:

1) Simulation

2) Dynamic programming and its variants

3) Linear programming, network flow, and nonlinear programming

4) Aggregation and Decomposition

Simulation

Several earlier studies have developed simulation models to determine the operating policies. Necessary inputs required in the models are sequence of inflows and a set of predetermined reservoir release rules. Examples of this work can be found in Askew et al. (1962), Maass et al. (1962), Hufschmidt and Fiering (1966), Toebes and Chang (1972), and Perez et al. (1970). Although simulation models are very flexible, they are also very costly and generally do not provide optimal policies. Thus, application of simulation alone does not seem to be appropriate in finding optimal policies.

The general conclusion among researchers in this area is that simulation may be used to check the policies obtained from other optimization routines. This approach is very valuable and has been used in many studies such as Karamouz and Houck (1982), Can and Houck (1984), McKerchar (1975), Young (1967), and Sigvaldason (1976).

Dynamic Programming (DP) and Its Variants

Dynamic Programming (DP) is probably the most widely used technique in the area of reservoir management. This is due to its ability to handle nonlinearity efficiently, its computational attractiveness, and its unique procedure in breaking a problem into smaller subproblems which utilize the "principle of optimality." The concept of "principle of optimality" fits very well with the reservoir operation problem. Typically, the planning horizon is broken down into subproblems, one for each time period. The problem is solved according to period one, then period two is considered using the solution obtained from period one as the input, and so on until the last period of the planning horizon is reached. The solution from the last time period provides the optimal solution for the whole problem. The general concept of DP was introduced by Bellman (1957). In addition to this book, there are several excellent references which provide the explanations about DP such as Larson (1968), Bellman and Dreyfus (1962), Dreyfus and Law (1978), and Denardo (1982).

The first published article which used DP to solve the deterministic reservoir operation problem is by Young (1967). In his work, DP was used to solve for the optimal releases from a reservoir according to different sets of inflows. Regression analysis was then performed to provide general operation rules for the reservoir. Among the work which employed DP are Hall et al. (1968), Fitch et al. (1970), Fults et al. (1976), Collins (1977), Austin and Glanville (1979), Moore and Yeh (1980), Bhaskar and Whitlach (1980), and Karamouz and Houck (1982).

Typically, in these applications, DP is used to find the optimal releases for a sequence of historical inflows. Consider the single-reservoir system presented earlier in this chapter, the recursive equation for the DP formulation is of the form:

$$f_t(S_t) = \underset{R_t}{\text{Max}} \; [r(R_t) + f_{t-1}(S_{t-1})] \qquad (2.4)$$

where

$f_t(S_t)$ = total optimal return incurred from the beginning of the operation until the end of period t when the storage at the end of period t equals S_t.

$r(R_t)$ = return associated with release R_t during period t.

The constraints and notations are the same as constraints (2.1) - (2.3).

According to DP terminologies of stage, state, and decision, the time period is treated as stage, the storage level of the reservoir as state, and the release as decision. For multiple-reservoir systems, the problem has multiple states rather than a single state. Each state variable corresponds to the storage level in each reservoir. For example, if there are three reservoirs in the system there will be three associated state variables to be considered at each stage (time period).

In order to apply the conventional dynamic programming computational procedure, there must be a finite number of admissible states and admissible controls. This requirement is usually met by discretizing these variable (Larson, 1968). Thus, for problem with continuous variables such as the reservoir operation problem, the typical approach is to provide a range of representative discrete values for each variable. Although this discretization scheme does not pose much difficulty for problems with single state variable, it becomes prohibitively burdensome in problems with multiple state variables. For example, consider a system of n reservoirs with k possible storage levels for each reservoir, in order to cover all the possible states at each stage, the memory requirement for each stage is k^n. With k=10 and n=6, there are 10^6 states to be covered. This illustrates that the computational and memory requirements in the conventional DP increase exponentially as the number of state variables increases. The computational difficulty associated with DP in dealing with multiple state variable problems is referred to as the "curse of dimensionality". Thus, for problems with multiple state variables, it is very important to provide an appropriate number of discrete values for each variable, since too many of them will lead to computational difficulty while too few of them can lead to incorrect solutions. For the reservoir operation problem, it is generally agreed that the conventional DP may be effectively applied to small systems of one or at most two reservoirs only.

From this point, the DP approach discussed so far will be referred to as the conventional DP (CDP) to differentiate it from its extensions.

One of the most active areas of research in the reservoir operation problem is the attempt to overcome the "curse of dimensionality." Several variations of CDP have been developed and applied to the deterministic reservoir operation problem with various degrees of success. The following are important algorithms which have been proposed:

1) State incremental dynamic programming (SIDP)
2) Discrete differential dynamic programming (DDDP)
3) Constrained differential dynamic programming (CDDP)
4) Progressive optimality algorithm
5) Binary state dynamic programming (BSDP).

All these schemes are "successive approximation" algorithms. That is, an initial solution which specifies the release schedule for each time period must be provided by the user. The successive approximation describes how to construct from the initial solution a new release schedule, which in turn, serves as an input release schedule for the next run. Thus, new release schedules (or trajectories) are successively constructed according to the algorithm until some convergence criterion is satisfied.

In SIDP, with an initial trajectory corresponding to a system of n reservoirs, the algorithm fixes the n-1 reservoirs at their levels and varies only the state of one reservoir. The solution from this iteration is used as the input for the next iteration in which a new state according to another reservoir is chosen to be varied while the other n-1 states are fixed. The algorithm continues this way until there is no significant improvement. Thus, the problem is reduced from n dimensions to only one dimension. Larson (1968) applied this "one-at-a-time" approach to a system of six reservoirs. Korsak and Larson (1970) provided the proofs of convergence for this approach. Some of the work which employed SIDP to the reservoir operation problem are Trott and Yeh (1973), TVA (1977a), and Becker et al. (1976).

The DDDP procedure was first described by Hall et al. (1969a,b) under a different name. The name DDDP is due to Heidari et al. (1971). With a given initial trajectory, the algorithm analyzes only the states that are small increment ΔS_t above and below the given value of each state variable. In other words, each state variable can take only three values: $S_t - \Delta S_t$, S_t, and $S_t + \Delta S_t$ for the next iteration. The small increment of ΔS_t above and below each state level is referred to as the "corridor." The corridor can be successively narrowed until the convergence criterion is satisfied. Thus, DDDP reduces the number of states to be covered at a stage to 3^n, where n is the number of reservoirs. It may be noticed that if n is large, DDDP still suffers from the "curse of dimensionality." Applications of DDDP to the reservoir operation problem are shown in Hall et al. (1969a,b), Heidari et al. (1971), Meredith (1975), Chow et al. (1975), Singh (1978). Nopmongcol and Askew (1976) extends the concept of DDDP through the introduction of a multilevel approach. Their algorithm uses SIDP to find a reasonable policy which is used as an initial trajectory. Then, instead of the "one-at-a-time" approach they suggested "two-at-a-time" or higher levels which tend to converge faster.

Murray and Yakowitz (1979) indicated that SIDP can overcome the curse but its convergence rate is slow. DDDP, however, can only reduce the computational burden but cannot actually eliminate the curse. They proposed a new algorithm, CDDP, which has a faster convergence rate and does not suffer from the curse. The algorithm proceeds by constructing an approximation to the benefit function in the neighborhood of the state arrived at during the previous iteration, and adjust the control variables so as to maximize the value of the approximating function. This is done for each stage, working backwards from the end of the control period to the beginning. The whole process is then repeated for the next iteration. The benefit is approximated by a linear or quadratic function constructed from a Taylor series so as to avoid solving a difficult nonlinear optimization problem at each step. The memory requirement of CDDP is proportional to n^2 and the computational time varies with n^3, where n is the number of reservoirs. Murray and Yakowitz (1979) applied CDDP to systems of four and ten reservoirs.

Closely related to the concept of DP is the so-called "progressive optimality algorithm" introduced by Howson and Sancho (1975) and applied to the reservoir operation problem by Turgeon (1981a). Analogous to the "principle of optimality," it states that a trajectory is optimal if and only if each pair of adjacent decision sets is optimal with respect to its initial and terminal states. Thus, to find the optimal trajectory, the storages at time t and t + 2 are held constant while those at time t + 1 are varied to maximize the total benefit function, for all periods. This procedure is repeated until convergence is reached. Convergence rate is quite slow and a good initial trajectory is very desirable. The major advantages of this algorithm are that the state variables do not have to be discretized, convergence to at least a local optimal solution is guaranteed, and it is easy to program and fast to execute.

Ozden (1984) considered the two techniques, CDDP and the progressive optimality algorithm, to be the most efficient techniques among the variations of CDP. However, he pointed out that both techniques require that the objective function be differentiable and constraints be linear. He then proposed a new algorithm, BSDP, and applied it to a four-reservoir system. The algorithm is similar to CDDP but the level of a state for the next iteration is provided by a proper combination of the two levels of that state in the current iteration. The Taylor series is not used in BSDP.

With the above mentioned variations of CDP, the limitation in solving large-scale systems due to the "curse of dimensionality" can now be overcome. However, one important factor which may cause some difficulty is in providing the initial trajectory. With poor initial trajectories, these algorithms may not converge or may be trapped with inferior local optimal solutions.

It is also important to mention that all the variations of CDP proposed so far can be applied to deterministic systems only. In the stochastic case where inflows are not known with certainty but take on values corresponding to their assigned probabilities, there is no "one-to-one" correspondence between the state and decision variables anymore. Thus, the "successive approximation" approach in which a new trajectory is based on the previous trajectory is no further applicable. At present, only CDP can be used in the stochastic case.

Linear Programming (LP), Network Flow, and Nonlinear Programming (NLP)

The major advantages of LP are that it can handle a large number of variables and constraints, and programming requirements are minimum since there are a number of commercial LP codes available. The major drawback of LP is obvious, it requires linearity in both the objective function and constraints. When nonlinearity is present it is necessary to use some linearization schemes to obtain the approximate solution. Some of the works which apply LP to the reservoir operation problem are Drobney (1971), Mejia et al. (1974), Draper and Adamowski (1976), and TVA (1977b). When LP is used to solve a very large system the computational time often takes very long. For example, Draper and Adamowski (1976) applied LP to a system of 17 reservoirs. The model consists of 872 constraints and 433 variables. They reported that the computations took so long that the problem was run only four times and was used as a screening model to indicate which reservoirs should be included in a simulation model.

LP has also been used to solve subproblems in higher level routines. Becker and Yeh (1974) developed a combined LP/DP model to optimize the operation of a multiple-reservoir system. In the algorithm, DP is used to select the optimal reservoir storage policy path through the sequence of policy periods, while LP optimizes within each period. Extensions of this model are provided in Yeh et al. (1979), and Mohammadi and Marino (1984).

Network flow algorithms are closely related to LP. They are specialized algorithms which take advantage of special structures of problems which are to be solved. Most of the network flow models can be formulated as LP models. However, the time required to solve a problem using a network flow algorithm is usually much less than the time needed by its corresponding LP formulation. Evenson and Mosely (1970), Jensen et al. (1974), and Boshier and Lermit (1977) applied linear network flow algorithms to the reservoir operation problem. Martin (1980) and Rosenthal (1981) used nonlinear network codes for nonlinear-reservoir systems.

Unlike LP, there is no standardized algorithm in the case of NLP. The user has to decide which NLP algorithm, among various available algorithms, should be used. The ones which are popular in the reservoir operation problem are reduced gradient, conjugate gradient, gradient projection, and Lagrangian methods. Some of the studies in this direction are Lee and Waziruddin (1970), Gagnon et al. (1974), Hicks et al. (1974), TVA (1976), Chu and Yeh (1978), and Hanscom et al. (1980).

Aggregation and Decomposition

The aggregation approach attempts to reduce the dimensionality of the problem by aggregating a number of reservoirs into an equivalent single reservoir. Thus, a system with a large number of reservoirs may be reduced to a smaller system with a few big reservoirs. After the solution of the reduced system has been obtained, it is then disaggregated back to provide the solution for each individual reservoir. Normally, reservoirs in series, i.e. they are located on the same river, are aggregated into a single reservoir. Smith (1981) and Fontane (1982) are examples of this approach.

Decomposition is another way of reducing the problem size. In this approach, a large-scale problem is broken down into smaller sub-problems. Roefs and Bodin (1970) and Bodin and Roefs (1971) used Dantzig-Wolfe decomposition for the solution of a nonlinear reservoir system. A multilevel approach in which subproblems are decomposed into several levels has been considered in Opricovic and Djordjivic (1976), Pratishthananda and Bishop (1977), and Bonazountas and Camboulives (1981). Coskunoglu and Adiguzel (1980) introduced the concept of decentralization as a basis for decomposition. They assumed that the reservoir manager plans for the whole system but each operator is responsible for the actual operation of each reservoir. Thus, the system is controlled by two types of agents of different control intervals, authorities, and responsibilities.

There are some drawbacks of the approaches in this direction. First, they require a large amount of information which is normally unavailable and rather difficult to collect. Second, they tend to depend highly on the system configuration. Inappropriate objective functions in the master problem and various subproblems, and unsuitable parameters used as the basis for aggregation or decomposition can lead to meaningless results. Third, they are relatively complex and actual implementation may not be easy. Fourth, they do not seem to be appropriate for multiple-objective models since it is difficult to identify a common unit for various purposes which may be used as a basis for aggregation or decomposition.

Systems With Single Objective and Stochastic Inflows

A large amount of work is also apparent in this direction although not as extensive as in the deterministic case. Optimization methodologies which have been developed and applied to the stochastic reservoir operation problem may be grouped into the following classes:

1) Stochastic dynamic programming and its variants
2) Chance-constrained programming and extensions
3) Stochastic programming
4) Aggregation and decomposition

Stochastic Dynamic Programming (SDP) and Its Variants

The earliest SDP model of the reservoir system in English language appears to be the work of Little (1955) which, surprisingly, precedes applications of deterministic DP by over a decade. When inflows are treated as stochastic none of the variations of DP introduced in the deterministic case can be used. Thus, SDP formulations can only be solved by the conventional DP. As a result, SDP is suitable for single-reservoir systems only.

A typical SDP formulation is similar to the deterministic case. The only difference is that uncertainty is incorporated into the recursive equation of SDP formulation. Thus, instead of equation (2.4), the recursive equation of the SDP formulation becomes:

$$f_t(S_t,I_t) = \max_{R_t} [r(R_t) + \sum_{I_t} P(I_t|I_{t-1}) \cdot f_{t-1}(S_{t-1},I_{t-1})] \quad (2.5)$$

where

$f_t(S_t, I_t)$ = total return at the end of period t when the storage at the end of period t is S_t and the inflow during period t is I_t.

$P(I_t | I_{t-1})$ = probability that the inflow during period t is I_t provided that the inflow during period t-1 is I_{t-1}.

The other terms are the same as in the deterministic DP formulation.

Thus, the state in SDP is characterized by both the storage and inflows rather than storage alone. This is because inflows are no longer assumed to be known with certainty. The probability term in the recursive function assumes that the current inflow is dependent on the last period inflow only. Ideally, the formulation should consider the case that the current inflow may be dependent on all the previous inflows from the beginning of the planning horizon. However, this ideal case leads to computational infeasibility since the memory and time requirements far exceed the capacity of today's computers. This is the reason why most of the SDP formulations consider only one period correlation of inflows. Examples of the work in this direction are Little (1955), Schweig and Cole (1968), Butcher (1971), Croley (1974a), and El-Tayeb (1983).

Closely related to SDP is the Markov decision process (MDP) approach. Note that the assumption about the current inflow being dependent only on the last period inflow is the Markov assumption, i.e. the probability transition term may be written as:

$$P(I_t | I_{t-1}, I_{t-2}, \ldots, I_1) = P(I_t | I_{t-1})$$

One type of MDP which may be adapted to solve the reservoir operation problem is the discrete time, infinite planning horizon, and stationary model. The requirement for discrete time is because decisions are made at evenly spaced epochs. The system is assumed to be operated over a very long period of time, i.e. infinite horizon. Finally, the return function, $r(R_t)$, and the probability term $P(I_t|I_{t-1})$, are assumed to be independent of the number of periods that have elapsed since decision making began. For example, if the state (which consists of storage and inflow) corresponding to May and October is the same and if the same amount of release for May and October is made, then the benefits obtained from the two months must be the same. Thus, in addition to the Markov assumption, two more assumptions, namely, infinite planning horizon and stationarity are required in typical MDP models. More comprehensive descriptions of MDP can be found in Howard (1960), Ross (1970), Bertsekas (1976), and Denardo (1982).

However, the stationarity assumption does not seem to be appropriate with the reservoir operation problem since the effect of seasonality plays an important role in the results. It is highly unlikely that the same amount of benefit will be gained in the above case. Su and Deininger (1972) modified the stationarity assumption to periodicity assumption. This may be simply explained as follows: suppose all the months considered here are in the same state, and if the release for each month is the same, then the benefit gained from the same month of any year will be the same. For example, the benefit gained in May, 1972 is the same as in May, 1980 or May, 1984, but not the same as in October, 1972; December, 1982; etc. The discrete time, infinite planning horizon, periodic MDP models of the reservoir operation problem are shown in Su and Deininger (1974), Mawer and Thorn (1974), Roefs and Guitron (1975), Bogle and O'Sullivan (1979), Bras et al. (1983), and Stedinger et al. (1984).

Another variation of SDP which assumes that inflows are independent random variables, i.e. correlation between the current inflow and the previous inflow is assumed to be insignificant, has been considered by Gessford and Karlin (1958), Russell (1972), Askew (1974,1975), Rossman (1977), Hinks (1977), and Sniedovich (1979,1980). The motivation for this assumption is that it leads to much more elegant and relatively easily computed solution strategies. This independence assumption is regarded as one of the important controversies in the reservoir operation literature. Yakowitz (1982) indicated that results from the testing of the Markov assumption on rivers of the southwest by various researchers show that on a weekly basis the independence assumption may be tenable, but not on a daily basis.

SDP and its extensions are excellent approaches for single-reservoir systems. They may be applied to two-reservoir systems with some computational difficulty. With larger systems they become highly inefficient or even infeasible due to the "curse of dimensionality."

Chance-Constrained Programming (CCP) and Extensions

Chance-constrained programming (CCP) is another optimization methodology which has gained considerable attention in the area of stochastic reservoir system. In this approach, constraints which involve random variables are not expected to be satisfied with certainty but only with given probabilities. For example, instead of stating that the storage level during period t must not exceed the maximum allowable storage level, it may be stated that the probability that the storage level during period t do not exceed the maximum allowable storage level is at least 95 percent. The probability level is normally determined by the user of the model. This may be simply expressed mathematically as follows: consider the constraint of maximum allowable storage level, i.e. constraint (2.2) which is repeated here for convenience,

$$S_t \leq S_{max} \qquad t = 1,2,...,T \qquad (2.2)$$

Recall the continuity equation,

$$S_t = S_{t-1} + I_t - R_t \qquad t = 1,2,...,T \qquad (2.1)$$

Substituting (2.1) into (2.2)

$$S_{t-1} + I_t - R_t \leq S_{max} \qquad t = 1,2,...,T \qquad (2.6)$$

Since I_t is now a random variable, constraint (2.6) cannot be expected to be satisfied with certainty. In the CCP approach, it is transformed into,

$$P(S_{t-1} + I_t - R_t \leq S_{max}) \geq \alpha \qquad t = 1,2,...,T \qquad (2.7)$$

where α is the probability level to be specified.

Thus, any function which involves random variables must be transformed into the form of constraint (2.7) which is referred to as the "chance-constraint." The various chance-constraints are then converted to their "deterministic equivalents" from which random variables are eliminated. The conversion of some chance-constraints can lead to very complex deterministic equivalents. This approach is used in Curry et al. (1973), Lane (1973), and Eisel (1972).

Revelle et al. (1969) extended the concept of CCP by incorporating a linear decision rule into the formulation. The linear decision rule of the form $R_t = S_t - b$ was proposed. The optimal value of the variable b is to be determined. The use of this linear decision rule reduces the size of the problem considerably. Some of the studies which employed the concept of linear decision rule are Revelle and Kirby (1970), Joeres et al. (1971), Nayak and Arora (1971). Despite its usefulness, this approach has been criticized as providing conservative operating policies, i.e. it more than satisfies the constraints of the model (Loucks and Dorfman, 1975). This is mainly due to the correlation between inflows in succeeding months being ignored. Several studies have attempted to alleviate this conservativeness. Gundelach and Revelle (1975) proposed an extended linear decision rule which results in a less conservative model. Houck (1979) introduced multiple linear decision rules, each conditioned on any desired season's inflows in the formulation. Joeres et al. (1981) proposed a new linear decision rule which incorporates explicit consideration of the correlation between inflows. Houck and Datta (1981) and Datta and Houck (1984) used decision rules which include inflows predicted by forecasting routines. Statistical properties of forecast errors for different steps are explicitly considered.

One difficulty in the CCP approach is pertained to the determination of appropriate probability levels for various constraints. Generally, it is assumed that the system manager is capable of providing appropriate values due to his experiences and familiarity with the system, which is not an unrealistic assumption. However, a better approach is to provide several probability levels for each important constraint and determine the corresponding results. Yazicigil and Houck (1984) employed this kind of sensitivity analysis in their multiple linear decision rule model. Another approach is to treat each probability level as a decision variable in the formulation rather than as a predetermined value. This approach is referred to as the "reliability programming" and was applied to the reservoir operation problem by Colorni and Fronza (1976), Simonovic and Marino (1980, 1981, 1982), and Marino and Mohammadi (1983).

Stochastic Programming

In this approach a problem is first treated as deterministic, then due to the randomness of some variables, a new formulation of the problem is solved based on the nature of the physical system and the randomness. Prekopa and Szantai (1974) proposed a multi-stage stochastic programming which considers several desirable characteristics. First, decisions are made sequentially in time, after every observation of the random variables belonging to the system. Second, past history of the system is used, i.e. considerations are based on conditional distributions. Third, probability distributions of random variables which will be realized in the future are taken into consideration. And fourth, the joint probability distribution of random variables instead of marginal distributions is considered. Applications of stochastic programming approach to the reservoir operation problem are shown in Peters et al. (1978), Prekopa (1975), Prekopa et al. (1978), and Sharda and Karreman (1981). In most of these works, joint chance-constraints are considered instead of individual chance-constraints. This is due to the argument that it is more realistic to consider the probability of the system failure during its entire planning horizon than to consider only one single period at a time. Thus, as an example, constraint

(2.7) which is normally written as,

$$P(S_{t-1} + I_t - R_t \leq S_{max}) \geq \alpha \qquad t = 1,2,\ldots,T \tag{2.7}$$

is now replaced by,

$$P(S_{t-1} + I_t - R_t \leq S_{max},\ t = 1,2,\ldots,T) \geq \alpha \tag{2.8}$$

Despite being more realistic, this approach does not seem to be popular among researchers in the reservoir operation system since the problem cannot be reduced into an easily solvable deterministic form.

Aggregation and Decomposition

The ideas of aggregation and decomposition are similar to the deterministic case discussed earlier. Thus the drawbacks of the deterministic case are also applied here. However, this approach seems to be more attractive when inflows are treated as stochastic since some other approaches, especially those related to dynamic programming, have difficulties when applied to large systems. If systems can be aggregated or decomposed into smaller subproblems, then techniques which are efficient in small-scale problems may be applied to each subproblem.

Aggregations and decompositions of stochastic reservoir systems were considered in Arvanitidis and Rosing (1970a,b), Turgeon (1980, 1981b), Quintana and Chikhani (1981), Soares et al. (1980), Boshier and Read (1980), and Gilbert and Shane (1982). The primary purpose of these systems are hydroelectric power generation.

Systems With Multiple Objectives and Deterministic Inflows

Recently, considerable attention has been directed toward the multiple-objective nature of the problem. However, the amount of work done in this case is much less than in the two previous cases.

In Chapter III, an overview and a classification of multiple-objective methodologies will be provided. With respect to the literature review in this section, only the techniques and their brief descriptions are discussed. The multiple-objective methodologies which have been employed to solve the reservoir operation problem with multiple objectives and deterministic inflows are:

1) Weighting technique
2) Constraint technique
3) Goal programming
4) Multiobjective linear programming

Weighting Technique

In this approach, different objectives are combined into a single objective by assigning the same utility measure to all of them. Relative importance of each objective is specified by its corresponding weighting factor. Normally, each weighting factor takes on values from zero to one and the sum of all weights must be unity. Trade-offs can be made by using a number of different sets of weights.

At first glance, one tends to think that a natural extension of any single-objective model to its corresponding multiple-objective model is by this technique. However, there is a number of difficulties which discourages this type of extension. First, as mentioned earlier, it is difficult to assign the same utility measure to all objectives. Second, if trade-offs are to be realistically performed, a large number of different sets of weights must be used for several runs. Third, it is not simple to provide suitable sets of weights which accurately reflect the relative importance among objectives. Fourth, when there are several objectives to be considered, which is typical in the reservoir operation problem, the computational requirement is very large since it increases exponentially as the number of objectives increases.

Ford et al. (1981) solved a two-reservoir system by nonlinear programming. Simulation was then used to verify the obtained results. In their trade-off analysis, the weighting method was employed. The objectives considered in their model are flood control, power generation, water supply, water quality maintenance, and recreation. Yazicigil et al. (1983) developed an LP-based optimization model for a system of four reservoirs. Three objectives based on target values were considered, i.e. deviations of storage from target levels at the reservoirs, deviations of flow from target levels at the control stations downstream of the reservoirs, and deviations of excessive rate of change of release values from allowable limits. Trade-offs were analyzed by applying the weighting technique to the first two objectives while holding the third objective fixed.

Constraint Technique

This approach can directly handle noncommensurate objectives. It treats one objective as the primary objective and considers the other objectives as constraints. Thus, the minimum acceptable levels of those objectives treated as constraints must be specified. Trade-offs can be made by varying the minimum acceptable levels of constraint-status objectives in different runs. Also, each objective may be switched from the primary objective to a constraint, and vice versa. There are some drawbacks in this approach. First, appropriate minimum levels of secondary objectives must be provided and varied from run to run. Second, assigning the status of a constraint to an objective may not reflect the relative importance of the objective to others. Finally, the computational burden of this approach also increases exponentially with increasing number of objectives.

Tauxe et al. (1979a,b) combined the concept of dynamic programming with the constraint method. They referred to this approach as "multi-objective dynamic programming (MODP)". The model was applied to a single-reservoir system with two objectives. Yeh and Becker (1982) employed dynamic programming, linear programming, and constraint method to solve a multiple-reservoir system with five objectives which are hydropower production, fish protection, water quality maintenance, water supply, and recreation. Palmer et al. (1982) combined linear programming and constraint method to determine the yield of multireservoir water supply systems. In all these studies, the constraint method was used to assign primary and secondary objectives. Optimization techniques such as DP, combined DP/LP, or LP were then used to solve for the operating policies according to different runs. Croley (1974b) extended the constraint method by incorporating risks in the trade-off analysis. This method was designed for problems with two objectives. It enables estimation of risk associated with achievement of various levels of one objective while minimum levels of the other objectives are specified through objective trade-off determinations. The method was applied to a single-reservoir system in Iowa which is operated on the basis of flood control and recreation.

Goal Programming (GP)

Goal programming may be regarded as one of the most popular techniques employed to solve problems which involve multiple objectives. In GP, optimizations are performed in an hierarchical order in which objectives with higher priorities must be satisfied before lower priority objectives can be considered.

Dauer and Kruger (1979) solved a multiple-reservoir system using GP and constraint method. They divided the system into groups of objectives according to their priorities in the model. GP was used to analyze this system of groups, while the solution structure of each individual group was developed using the constraint method. Primary objectives were determined as budget considerations, flood control, and irrigation. Secondary objectives were recreation and wildlife benefits.

The idea of "target" values rather than economic-based objectives was considered in Chisman and Rippy (1977), Can and Houck (1974), and Datta and Burges (1984). In this approach, information from demands of water for various purposes, contracted amount of hydroelectric power generation, contracted amount of water for industrial uses, and suitable levels of water storage are used as the basis for determining appropriate goals. The system should be operated in such a way that deviations from the targets be minimized. This approach has one major advantage over the traditional economic-based approach, i.e. it does not require an extensive economic analysis, which is usually very difficult, in order to form objective functions.

Chisman and Rippy (1977) proposed a model with several goals which are flood control, irrigation, hydroelectric power generation, downstream low flow augmentation, industrial and municipal water supply, downstream navigation, and recreation. Can and Houck (1984) compared the results obtained from GP with another optimization model (LP) which was formulated earlier to solve the same problem of four reservoirs. They indicated that the operating rules from GP and LP were comparable in their effectiveness, although in some cases the GP operations were better. Both GP models are real-time models. The time step considered is daily. Also, perfect forecasts of future inflows are assumed. Datta and Burges (1984) considered the case of imperfect forecast in their GP formulation of a single-reservoir system.

Cohon (1978) indicated that the traditional GP approach may not be suitable for public decision-making problems. Normally, public systems are not designed or planned to generate a certain quantity of economic efficiency benefits. Thus, it is not appropriate for the managers of public systems to specify the desired levels of economic-based benefits. However, the approach of "target" values mentioned earlier does not suffer from this difficulty since the reservoir managers have a good idea of the appropriate target levels to be aimed for. So, applications of GP in this case seem to be justified.

All the GP models of the reservoir operation problem discussed so far have one thing in common: they require the reservoir manager to provide target values and priority information about various goals before the problem can be analyzed. The drawback of this approach, which is typical of the traditional GP technique, is that inferior solutions may be obtained if the reservoir manager cannot provide appropriate information which really reflect his utility due to the complexity of the system. One way to avoid this drawback is to allow the reservoir manager to participate during the problem solving session so he can modify his decision about target values and priority structure from one iteration to the next until a satisfactory solution is obtained. Thus, unlike the traditional GP approach which requires accurate preference information prior to the analysis, this approach assumes that, as the session continues, the reservoir manager becomes more familiar with the nature of the problem and can provide more accurate preference information.

In Chapter III, the concept of GP and an overview of its extension will be provided. The idea of interactive GP will be utilized in the solution procedures for this research.

Multiobjective Linear Programming (MOLP)

This technique is the direct extension of linear programming in order that more than one objective be considered. It can be used to generate an exact representation of the nondominated set. This is done by moving mathematically from one nondominated extreme point to adjacent nondominated extreme points until all of them have been found. A nondominated point is a point at which no increase in the achievement of one objective can be made without decreasing one or more of the achievements in other objectives.

Gries et al. (1983) solved a multiple-reservoir system with six objectives. An interactive approach which combines MOLP and Tchebycheff techniques was used. The Tchebycheff technique was introduced to find the solutions of highest utility which may not correspond to extreme point solutions.

Summary

From the literature review, it can be seen that the researchers in this area have different viewpoints about the characteristics of the reservoir system. There are several approaches used and developed to solve the problem. Each approach has its share of advantages and drawbacks.

Among models which consider only one objective and treat inflows as deterministic, there are several techniques which can effectively solve the problem. Constrained differential dynamic programming (CDDP), binary state dynamic programming (BSDP), the principle of progressive optimality, and network flow algorithms deserve attention due to their ability to handle large-scale systems and their computational efficiencies. Simulation does not seem to be an appropriate technique in determining optimal operating policies but proves to be very useful as a tool to check the optimal operating policies obtained from various optimization techniques. Aggregation and decomposition approaches tend to complicate the problem further due to their requirements of a large amount of information. Various studies in this case are listed in Table I.

In the case of single objective and stochastic inflows, there are relatively fewer efficient techniques. Stochastic dynamic programming (SDP) can handle only small systems of one or at most two reservoirs. No extended algorithms of DP in the deterministic case can be applied here. Approaches of chance-constrained programming seem to be most appropriate in this case. However, the problem of model conservativeness due to the independent inflows assumption needs to be overcome. Thus, correlations between inflows should be recognized which make the problem more complex. Despite being more realistic, the stochastic programming approach has not gained much attention due to its high complexity. Approaches of aggregation and decomposition seem to be more justified here since there is no general algorithm which can handle large-scale problems efficiently as in the deterministic case, provided that the required information can be obtained. Table II summarizes the research efforts in this case.

Multiple-objective models have gained considerable attention recently. The multiple-objective methodologies which have been used to solve the reservoir operation problem are weighting method, constraint method, goal programming (GP), and multiobjective linear programming (MOLP). Difficulties in forming appropriate objective functions due to unavailability of data and complexities of the system seem to be the motivation for considering only one objective in earlier studies. However, the use of target-based objectives rather than economic-based objectives can overcome these difficulties greatly. Targets may be derived from the available information such as demands of water for various purposes, contracted amount of energy, and desirable levels of reservoir storages. GP seems to be a very appropriate technique for this type of problem. In order to alleviate the drawback of the traditional GP technique, an interactive version of GP which allows participation from the reservoir manager during the analysis should be considered. Studies of deterministic reservoir systems with multiple objectives are listed in Table III.

In this study, a fourth class of model which considers multiple objectives and treats inflows as stochastic is proposed. At present, very little attention has been paid to this case. The development of this model is provided in Chapter IV. In the next chapter, an overview and a classification of multiple-objective methodologies is presented so that their concepts and underlying philosophies can be appreciated.

TABLE I

STUDIES OF SYSTEMS WITH SINGLE OBJECTIVE AND DETERMINISTIC INFLOWS

Simulation	DP and Its Variants	LP, Network Flow, NLP	Aggregation and Decomposition
	CDP	LP	
Askew et al. (1961)		Drobney (1971)	Roefs & Bodin (1970)
Maass et al. (1962)	Young (1967)	Majia et al. (1974)	Bodin & Roefs (1971)
Hufschmidt & Fiering (1966)	Hall et al. (1968)	Draper & Adamowski (1976)	Opricovic & Djordjivic (1976)
Perez et al. (1970)	Fitch et al. (1970)	TVA (1977b)	Pratishthananda & Bishop (1977)
Toebes & Chang (1972)	Fults et al. (1976)	LP/DP	Coskunoglu & Adiguzel (1980)
	Collins (1977)	Becker & Yeh (1974)	Bonazountas & Camboulives (1981)
	Austin & Glanville (1979)	Yeh et al. (1979)	Smith (1981)
	Moore & Yeh (1980)	Mohammadi & Marino (1984)	Fontane (1982)
	Bhaskar & Whitlach (1980)	Network Flow	
	Karamouz & Houck (1982)	Evenson & Mosely (1970)	
	SDDP	Jensen et al. (1974)	
	Larson (1968)	Boshier & Lermit (1977)	
	Trott & Yeh (1973)	Martin (1980)	
	TVA (1977a)	Rosenthal (1981)	
	Becker et al. (1976)	NLP	
	DDDP	Lee & Waziruddin (1970)	
	Hall et al. (1969a,b)	Gagnon et al. (1974)	
	Heidari et al. (1971)	Hicks et al. (1974)	
	Meredith (1975)	TVA (1976)	
	Chow et al. (1975)	Chu & Yeh (1978)	
	Singh (1978)	Hanscom et al. (1980)	
	Nopmongcol & Askew (1976)		
	CDDP		
	Murray & Yakowitz (1979)		
	Progressive Optimality		
	Turgeon (1981a)		
	BSDP		
	Ozden (1984)		

TABLE II

STUDIES OF SYSTEMS WITH SINGLE OBJECTIVE AND STOCHASTIC INFLOWS

SDP and Its Varients	CCP and Extensions	Stochastic Programming	Aggregation and Decomposition
Correlated Inflows	*CCP*		
Little (1955)	Eisel (1972)	Peters et al. (1978)	Arvanitidis & Rosing (1970a,b)
Schweig & Cole (1968)	Lane (1973)	Prekopa and Szantai (1974)	Turgeon (1980, 1981b)
Butcher (1971)	Curry et al. (1973)	Prekopa (1975)	Soares et al. (1980)
Croley (1974a)	*Linear Decision Rule*	Prekopa et al. (1978)	Boshier & Read (1980)
El-Tayeb (1983)	Revelle et al. (1969)	Sharda & Karreman (1981)	Quintana & Chikhani (1981)
MDP	Revelle & Kirby (1970)		Gilbert & Shane (1982)
Su & Deininger (1974)	Joeres et al. (1971)		
Mawer & Thorn (1974)	Nayak & Arora (1971)		
Roefs & Guitron (1975)	Loucks & Dorfman (1975)		
Bogle & O'Sullivan (1979)	Gundelach & Revelle (1975)		
Bras et al. (1983)	Houck (1979)		
Stedinger et al. (1984)	Joeres et al. (1981)		
Independent Inflows	Houck & Datta (1981)		
Gessford & Karlin (1958)	Datta & Houck (1984)		
Russel (1972)	Yacizigil & Houck (1984)		
Askew (1974, 1975)	*Reliability Programming*		
Rossman (1977)	Colorni & Fronza (1976)		
Hinks (1977)	Simonovic & Marino (1980, 1981, 1982)		
Sniedovich (1979, 1980)	Marino & Mohammadi (1983)		

TABLE III

STUDIES OF SYSTEMS WITH MULTIPLE OBJECTIVES AND DETERMINISTIC INFLOWS

Weighting Technique	Constraint Technique	GP	MOLP
Ford et al. (1980)	Croley (1974)	Chisman & Rippy (1977)	Gries et al. (1983)
Yazicigil et al. (1983)	Tauxe et al. (1979a,b)	Dauer & Krueger (1979)	
	Yeh & Becker (1982)	Can & Houck (1984)	
	Palmer et al. (1982)	Datta & Burges (1984)	

CHAPTER III

DECISION MAKING WITH MULTIPLE OBJECTIVES

Introduction

Multiple-objective decision making (MODM) is a branch of operations research methodologies which has gained much attention during the past fifteen years. In contrast to the traditional single-objective analysis in which the optimal solution is identified according to only one objective, a typical MODM methodology attempts to find one or more solutions which are most appropriate to a set of objectives being considered. In MODM analysis, there is usually no single best solution with respect to all objectives, thus the word "optimal solution" does not seem to be meaningful in the sense of MODM analysis. Rather, the most satisfactory solutions based on various competing objectives are normally referred to as "nondominated", "noninferior", or "Pareto optimal" solutions. A nondominated solution may be defined as a feasible solution for which an increase in value of any one objective can be achieved only at the expense of a decrease in value of at least one other objective (Zeleny, 1982).

There are several MODM methodologies which have been developed to solve problems in various areas. Comprehensive description of MODM and overview of MODM methodologies are presented in Zeleny (1982), Cohon (1978), Hwang et al. (1979), and Goicoechea et al. (1982). Cohon and

Marks (1975) evaluated the suitability of various MODM methodologies to water resources problems.

In this chapter, a classification of varius MODM methodologies will be discussed briefly in order to provide some idea about their underlying concepts. An overview of one technique, namely, goal programming, together with its extensions will be presented next since it is the basis of the methodology developed in this research.

Classification of Multiple-Objective Methodologies

MODM methodologies may be classified according to the articulation of the decision maker's preference structure. The time at which preference information needs to be provided by the decision maker is normally used as the basis for classifying various methodologies. Based on this parameter, there are three general classes of MODM methodologies as follows (Zeleny, 1982):

1) Methodologies that rely on prior articulation of preferences. An underlying assumption is that all necessary information about a decision maker's preferences can be extracted prior to the actual problem solving, independently of a given decision situation. In this view, human preferences are relatively fixed and consistent. There is no significant learning process. Examples of this class of methodologies are goal programming, multiattribute utility theory and its variants.

2) Methodologies that rely on progressive articulation of preferences. They assume that the decision maker is not able to provide a priori preference information because of the complexity of the system, but as the analysis continues he becomes more familiar with the system

and can provide his preference information more accurately. All interactive MODM techniques belong to this class.

3) Methodologies with posterior articulation of preferences. In this approach, the decision maker does not provide his preferences until the problem is solved. Then, based on the whole set of nondominated solutions identified by this class of MODM techniques, it is assumed that he will be able to select the one which is most satisfactory to him. This approach includes linear multiobjective programming, weighting method, and constraint method.

Each of the three classes of MODM methodologies has its share of advantages and drawbacks. For methods with posterior articulation of preferences, the advantage is that the decision maker can wait until the end of the analysis at which there are generally several nondominated solutions to be selected. By not limiting the number of nondominated solutions to only a few, it is believed that the decision maker will have the chance to select the solution which really reflects his preference structure. The drawback is that many real world problems are so large that it requires extremely large amount of time to generate the whole set of nondominated solutions. It also becomes more difficult for the decision maker to analyze the problem effectively when the number of nondominated solutions becomes too large. Methods with prior articulation of preferences, on the other hand, locates only one or a few nondominated solutions based on the decision maker's preferences. Thus, much computational time is saved since only a small portion of the nondominated set is considered. The major criticisms of this approach are due to the assumption that the preference structure of the decision maker remains fixed throughout the analysis, and the assumption that he can provide appropriate preference structure prior to solving the problem. In many cases, especially those related to policy planning in public sectors, the decision maker may not be able to identify preferences that really reflect his utility before he has some information regarding various alternative solutions. The interactive approach, i.e. those MODM methodologies with progressive articulation of preferences, tries to alleviate the drawbacks of the other two approaches by allowing the decision maker to provide his preferences during the problem solving session rather than before or after the session. The decision maker is usually required to iteratively interact with the algorithm in order to obtain the nondominated solution he most prefers. Thus, he is relieved from the burden of having to provide accurate preference information prior to the analysis. In addition, he can modify his preference structure from iteration to iteration if it is desirable. This approach does not suffer from excessive computational requirement since at each iteration the algorithm considers only the region of nondominated set which is closely related to the decision maker's current preference structure. The disadvantages of this approach, however, are that it requires more time and effort from the decision maker, and it becomes less effective with large scale problems.

Goal Programming and Extensions

Goal programming (GP) is a method which requires a priori articulation of preferences. It is closely related to linear programming and is considered to be one of the most popular MODM techniques. It has been extensively used in solving problems in such areas as production planning, manpower scheduling, capital budgeting, and transportation.

The concept of GP was first introduced by Charnes and Cooper (1961). Ijiri (1965) presented a definition of preemptive priority levels so as to treat goals according to their perceived importance. The preemptive version of GP was further extended by Lee (1972) and Ignizio (1976). A typical formulation of GP is as follows:

$$\text{Minimize} \quad \sum_{i=1}^{m} P_k(u_i p_i + v_i n_i) \qquad k=1,2,\ldots,K \tag{3.1}$$

Subject to

$$\sum_{j=1}^{N} a_{ij}x_j - p_i + n_i = T_i \qquad i=1,2,\ldots,m$$

$$x_j, p_i, n_i \geq 0$$

where

x_j = the j^{th} decision variable, $j=1,2,\ldots,N$.

p_i, n_i = positive and negative deviations from the target of goal i, respectively.

T_i = the target value according to goal i.

a_{ij} = technological coefficient associated with x_j in goal i.

P_k = the preemptive priority factor which expresses the relative importance of various goals, $P_k >> P_{k+1}$ for all k.

u_i, v_i = weighting factors corresponding to positive and negative deviations, respectively, which express the relative importance of goals within the same priority.

K = number of priorities.

m = number of goals.

N = number of variables.

Prior to the analysis, the decision maker is required to rank various goals according to their importance to him. Both positive and negative deviational variables, p_i and n_i, are to be minimized in order to achieve the solution which is as close as possible to the specified target. For a goal which underachievement is not desirable, n_i, must be included in the objective function according to the priority of that goal. Similarly, p_i, must be included in the objective function if overachievement is to be minimized. In GP, the underlying philosophy is based on "satisficing" rather than "optimizing". Instead of attempting to minimize or maximize various objective functions, GP is concerned with the conditions of achieving prespecified targets or goals. The solution procedure for the GP model consists of first minimizing the deviational variables with the highest priority level, P_1, to the fullest possible extent, the algorithm then proceeds hierarchically to lower priority levels, i.e. $P_2, P_3, \ldots, P_k$. In working with a particular priority level, if there is a solution which leads to degradation of the achievements in one or more of higher priority goals, then the solution is considered to be infeasible. When the lowest priority level, P_k, is completed, the solution to the problem is obtained.

There are two typical approaches for solving GP models. The first approach is referred to as "sequential linear goal programming" method. It involves a series of linear programming according to the order of priority levels. At each priority level, a linear programming is formulated to minimize the negative and/or positive deviations from prespecified targets. The constraints for the LP formulation are: all the goals corresponding to all priority levels up to the current level being considered, and another goal to assure that any solution to the current priority level cannot degrade the achievements obtained in the previous priority levels. Thus, for a K priority levels problem, there are K linear programming formulations to be solved in order to obtain the solution of the problem. The second approach is known as "multiphase linear goal programming" method. It is basically an extension of the two-phase method of conventional linear programming. It considers the problem as a whole rather than solving a series of linear programs. This generally results in fewer computations. The algorithmic steps of this approach are provided in Lee (1972), and Ignizio (1976). Although the multiphase approach tends to be more straightforward and more efficient than the sequential approach, most of GP applications employ the latter approach since there are LP computer packages which can handle large-scale problems. At present, computer codes for the multiphase algorithm can only be used for small to medium size problems. There are some recent research efforts which extend the existing multiphase algorithm in order to improve its computational efficiency and reduce its storage requirements. Arthur and Ravindran (1978) proposed a partitioning algorithm which consists of solving a series of linear programming subproblems, with the solution to the higher priority problems used as the initial solution to the lower priority problem. Computational economies are gained by considering only rows and columns affecting the most important unsatisfied goal. Schniederjans and Kwak (1982) proposed a new algorithm based on the concept of dual simplex algorithm. Olson (1984) modified Lee's algorithm (1972) by using the revised simplex method. The procedure operates with the initial identity matrix, updating other columns only as required. The objective function can be calculated for the most important unsatisfied objective level, and the contribution potential for each non-basic column can be generated without the need to compute the updated columns for other variables. At each iteration, the variables which cannot enter the solution at the next iteration (either because they are already in the basis, or because entering that variable would conflict with a higher objective level) are identified. Olson (1984) compared the four GP algorithms developed by Lee (1972), Arthur and Ravindran (1978), Schniederjans and Kwak (1982), and his revised simplex GP algorithm, by applying them to a series of 12 test problems. He concluded that both revised simplex and dual simplex algorithms appear to have computational advantages over Lee's full simplex code and Arthur and Ravindran's partitioning code. The dual simplex method appears to have superior computational times for models with a large proportion of positive deviational variables in the solution. The revised simplex algorithm appears more consistent in time and accuracy for general GP models.

In addition to the disadvantages of the prior articulation of preferences approach (that is, the decision maker's preference structure remains fixed throughout the analysis, he is assumed to be able to provide accurate preference information prior to the analysis, and only a few or even one nondominated solution is identified), GP suffers from two other criticisms. First, it can lead to dominated solution if the prespecified targets are too low. Second, a large amount of achievement levels in lower priority goals may result in order to attain higher priority goals. For example, a nondominated solution of (10,1000) according to the achievement levels of the first and second priority goals, respectively, is considered to be superior to another nondominated solution of (11,5). This is because higher priority goals must be treated before lower priority goals, and there cannot be any trade-off among them. In reality, however, the decision maker may be willing to increase a small amount of achievement levels in higher priority goals in order to obtain a large reduction in the achievement levels of lower priority goals. The drawbacks of GP can be alleviated greatly by allowing the decision maker to participate during the problem solving session. Thus, an interactive version of GP seems to be attractive since the decision maker can progressively provide his decision pertaining to the priority structure, target levels, and his preferred solution. In this way, the chance of obtaining a dominated solution is greatly reduced, and trade-off among the achievement levels of various priorities is possible. By combining the attractive features of both GP and interactive approaches, it is expected that the benefits gained can well compensate for the extra time and effort required from the decision maker during the analysis, provided that these requirements are not excessive. There is a number of interactive GP algorithms which have been proposed by various researchers. Dyer (1972) developed a model based on Frank-Wolfe algorithm. Fichefet (1976) proposed an algorithm called GPSTEM for solving linear MODM problems. Monarchi et al. (1976) introduced a method called SIGMOP. Masud and Hwang (1981) cited some drawbacks of these algorithms and proposed another algorithm called ISGP which guarantees nondominated solutions. In all these interactive GP algorithms, the objective functions need to be maximized or minimized. However, in some situations it may be desirable for a goal to be as close as possible to its target level. In these cases, algorithms which are based on a miximization or minimization routine tend to be inappropriate.

So far, only the determinisic case of GP model has been considered, that is, all the parameters in formulation (3.1) are assumed to be known with certainty. However, in many real world problems, some parameters are random variables and only follow certain types of probability distributions. When the problem is stochastic rather than deterministic, it usually requires additional effort in order to convert the problem to the standard form of GP, i.e. formulation (3.1). One approach, analogous to the case of linear programming, is to derive the "deterministic equivalents" of goals which involve random variables. An important assumption for this approach is that the probability distributions of random variables are known. This approach is referred to as "chance-constrained goal programming" and will be discussed in more detail in Chapter IV.

Summary

In this chapter, the general concepts of MODM have been discussed. Three major classes of MODM methodologies together with their advantages and disadvantages have been considered. The basic concept of GP on which this research is based, has also been presented. In order to alleviate the drawbacks of GP, an interactive GP, which combines attractive feaures of both GP and interactive approaches, seems to be an appropriate solution. In this approach, the decision maker can progressively provide his decision in order to achieve satisfactory solutions. Problems which involve random variables cannot be readily solved by GP but need to be converted to the standard GP formulation. One approach to deal with the stochastic case referred to as "chance-constrained goal programming" will be considered in Chapter IV. Also in Chapter IV, the model development of a typical reservoir system and the solution procedures for solving the problem will be presented.

CHAPTER IV

MODEL DEVELOPMENT AND SOLUTION PROCEDURES

Introduction

From the literature review in Chapter II, two methodologies which may be regarded as extensions of linear programming, referred to as chance-constrained programming (CCP) and goal programming (GP), have been employed in solving the reservoir operation problem. Each of these extensions was specifically developed to provide a better reflection of reality in the decision making process by relaxing particular assumptions which managers frequently find inappropriate. By introducing probabilistic constraints and deriving subsequent deterministic equivalents, CCP allows the direct consideration of random variables in the model. However, it was primarily designed for single-objective problems. On the other hand, GP allows the direct consideration of multiple goals which may be conflicting and noncommensurate. However, it requires all variables in the model to be deterministic. In this chapter, an approach based on the concepts of CCP and GP is considered. This approach, referred to as chance-constrained goal programming (CCGP), combines the advantages of both methods in such a way that it is capable of solving systems with multiple objectives and stochastic inflows.

To derive the deterministic equivalent of a chance-constraint, most of the existing chance-constrained models assume that the random variables are independent with known distribution functions. However, if the variables are correlated, the independence assumption can lead to less accurate results. In order to explicitly consider the correlation among random variables, conditional cumulative distribution functions instead of nonconditional cumulative distribution functions will be used in this research.

In this chapter, the development of a mathematical formulation for the research problem and its solution procedures are presented. First, the basic assumptions made in regard to the model formulation are documented. Various notations in the model and their definitions are also listed. With respect to the hydropower generation purpose, the appropriateness of treating the rate of energy generation and the power plant capacity as functions of the reservoir storage level is discussed. Next, the model formulation is provided. For constraints which involve the random variable, i.e. inflow, it is necessary to derive their deterministic equivalents. The development of conditional cumulative distribution functions of inflows are then presented. The subsequent section describes the chance-constrained goal programming formulation of the problem. Finally, the solution procedures to solve the proposed model are outlined.

Assumptions

The basic assumptions of the model are as follows:

1) The only random variable in the model is the inflow. The other variables, i.e. releases for various purposes, which are decision variables are treated as deterministic. This is due to the fact that the inflow is an uncontrollable parameter while releases are

controllable as long as the maximum capacity of the reservoir is not exceeded.

2) Demands for various purposes are assumed to be known and can be specified in the model prior to the analysis. For example, demands for M&I water supply and hydropower generation are normally set from contract requirements.

3) Evaporation from and absorption into the reservoir are assumed to be deterministic. Generally, the loss due to evaporation and gain due to absorption are much less than the contributions from other parameters. In many studies, evaporation and absorption are even assumed to be insignificant. The deterministic assumption is used in order to avoid unnecessary additional computations which are not likely to improve the accuracy of the solution. If inflow, evaporation, and absorption are assumed to be random variables, it is necessary to combine them by means of convolution.

4) The probability distribution function of the inflow in each period is assumed to be either normally or lognormally distributed. These probability distribution functions are adopted in many studies of the stochastic reservoir operation problem such as El-Tayeb (1983), Lane (1973), Sharda and Karreman (1981), and Prekopa et al. (1978).

5) The probability distribution function of the inflow in each period of the entire planning horizon is assumed to be the same.

6) Correlations among inflows in successive periods are assumed to exist. However, only one period correlation is assumed to be significant. Thus, the correlation between the inflow in each period and the next two periods or more are neglected.

7) With respect to the hydropower generation purpose, it is assumed that the rate of energy generation and the power plant capacity

can be expressed as functions of the reservoir storage level.

Assumptions 4-6 are generally adopted in most of the stochastic reservoir operation models. The appropriateness of these assumptions to a particular system may be verified by means of statistical analysis routines such as goodness-of-fit tests and regression analysis. The discussion of assumption 7 is provided after the description of various notations are listed.

Notations

The terms and their definitions used in the model are listed below:

$S_{j,t}$ = storage level of reservoir j at the end of period t.

$S_{j,max}$ = maximum capacity of reservoir j. This level must not be exceeded at any time since it will result in the system failure.

$S_{j,min}$ = minimum storage level, i.e. dead or inactive storage, of reservoir j.

$I_{j,t}$ = random inflow into reservoir j during period t.

$R_{j,t}$ = release through the power plant for hydroelectric power generation (or normal release for a nonpower reservoir) from reservoir j during period t.

$W_{j,t}$ = release for M&I water supply from reservoir j during period t.

$W_{j,min}$ = minimum required release for M&I water supply from reservoir j.

$W_{j,max}$ = maximum allowable release for M&I water supply from reservoir j.

$G_{j,t}$ = release through the spillway to maintain the maximum allowable storage in reservoir j during period t.

$D_{j,t}$ = downstream flow from reservoir j during period t.

$D_{j,min}$ = minimum required downstream water supply from reservoir j.

$D_{j,max}$ = maximum allowable downstream flow from reservoir j.

$EV_{j,t}$ = net evaporation from reservoir j during period t.

$MTAR_{j,t}$ = target water supply for M&I use from reservoir j during period t.

$DTAR_{j,t}$ = target water supply downstream from reservoir j during period t.

$PTAR_{j,t}$ = target hydroelectric power to be generated from reservoir j during period t.

$FC_{j,t}$ = flood control storage for reservoir j during period t.

$DC_{j,t}$ = drought control storage for reservoir j during period t.

$RCMAX_{j,t}$ = maximum storage of reservoir j during period t for recreational purpose.

$RCMIN_{j,t}$ = minimum storage of reservoir j during period t for recreational purpose.

$PMAX_{j,t}$ = power plant capacity of reservoir j during period t.

$n_{1,j,t}$ = negative deviation from goal 1 of reservoir j during period t.

$p_{1,j,t}$ = positive deviation from goal 1 of reservoir j during period t.

E = amount of hydroelectric power generated.

e = efficiency of the turbine ($o \leq e \leq 1$).

H = head acting on the turbine.

h = number of hours in the period.

k = conversion factor.

ξ = the rate of hydroelectric power generation.

$\alpha_{j,t}, \beta_{j,t}, \gamma_{j,t}, \eta_{j,t}$ = probability levels used in various probabilistic goals and constraints for reservoir j during period t.

F(.) = cumulative distribution function.

$F^{-1}(.)$ = inverse cumulative distribution function.

f = probability distribution function.

X,Y = random variables.

μ_X, μ_Y = means of X and Y, respectively.

σ_X, σ_Y = standard deviations of X and Y, respectively.

ρ = coefficient of correlation.

a_j, b_j = coefficients used to express the rate of hydroelectric power generation as a linear function of the storage of reservoir j.

c_j, d_j = coefficients used to express the power plant capacity as a linear function of the storage of reservoir j.

j = reservoir index, $j=1,2,\ldots,m$.

m = number of reservoirs in the system.

t = time period index, $t=1,2,\ldots,T$.

T = number of periods in the model.

l = goal index, $l=1,2,\ldots,L$.

q = priority index, $q=1,2,\ldots Q$.

L = number of goals in the model.

Q = number of priorities in the model.

P_q = the preemptive priority factor which expresses the relative importance of goal q, in general $P_q >> P_{q+1}$ for all q.

$u_{l,j,t}$, $v_{l,j,t}$ = weighting factors corresponding to positive and negative deviations, respectively, which express the relative importance of goal l of reservoir j during period t, if two or more goals have the same priority level.

Energy Rate and Power Plant Capacity as Functions of Reservoir Storage

Generally, the production of hydroelectric power during any period at any particular reservoir site is dependent on the installed plant capacity; the flow through the turbines; the average productive storage head; the number of hours in the period; the plant factor; and a constant for converting the product of flow, head, and plant efficiency to megawatt-hours of electric energy (Loucks et al., 1981). This can be expressed mathematically as,

$$E = eHRh/k \tag{4.1}$$

The rate of hydroelectric power generation, ξ, can be written as,

$$\xi = eHh/k \tag{4.2}$$

The head, H, itself is a function of the reservoir storage, S, and is given by,

$$H = S/AREA \tag{4.3}$$

where AREA is the surface area of the reservoir.

Equation (4.3) assumes that the head can be expressed as a linear function of the storage. This assumption is valid for reservoirs that have relatively large surface areas since they do not change greatly with changes in head. Consequently, from equation (4.2), the rate of hydroelectric power generation, ξ , which is a linear function of the head, can also be written as a linear function of the storage. The following linear function is used:

$$\xi = a + bS \tag{4.4}$$

Similarly, the power plant capacity is written as:

$$PMAX = c + dS \tag{4.5}$$

where a,b,c, and d are coefficients to be determined. For a particular reservoir, these coefficients are found by means of the regression analyses of the energy rate and the plant capacity versus the storage.

In dealing with reservoirs which are capable of generating hydroelectric power, there are two common approaches used to determine the amount of hydroelectric power produced in each period. The first approach is the more direct but time consuming approach, i.e. solve equation (4.1) which is a nonlinear function due to the product of H and R directly by available nonlinear programming algorithms. The obvious drawback of this approach is that much longer computational time is required by any nonlinear programming algorithm especially with large-scale problems. The second approach is to linearize equation (4.1) so that linear programming can be used. This approach is usually preferred to the first approach since a vast reduction in the computational time is expected. However, the accuracy of the solution depends highly on the approximating linear function. Loucks et al. (1981) indicated that the product of head and release through turbine during period t, i.e. H_tR_t, may be approximated as follows:

$$H_tR_t \cong \overset{o}{R}_t\overset{o}{H}_t + \overset{o}{R}_t(H_t-\overset{o}{H}_t) + \overset{o}{H}_t(R_t-\overset{o}{R}_t)$$
$$= \overset{o}{R}_tH_t + \overset{o}{H}_tR_t - \overset{o}{H}_t\overset{o}{R}_t \qquad (4.6)$$

where $\overset{o}{H}_t$ and $\overset{o}{R}_t$ are the average head and average release during period t, respectively.

The quantities $\overset{o}{H}_t$ and $\overset{o}{R}_t$ are to be estimated for each period t. The model may need to be solved several times in order to identify reasonably accurate average release and head estimates so that $R_t \cong \overset{o}{R}_t$ and $H_t \cong \overset{o}{H}_t$. Once $\overset{o}{R}_t$ and $\overset{o}{H}_t$ are reasonably accurate, the linear approximate, i.e. equation (4.6) is valid. Another linearization scheme recommended by Marino and Mohammadi (1983) is to derive the hydroelectric power production as a function of the reservoir storage. This scheme can be explained as follows: from equations (4.1) and (4.2), for each period t,

$$E_t = \xi_tR_t \qquad (4.7)$$

From equation (4.4), based on the storage level at the end of period t-1,

$$E_t = R_t(a+bS_{t-1}) \quad (4.8)$$

Using the continuity equation, i.e. equation (2.1), S_{t-1} can be determined. Thus, E_t is now a linear function of R_t only.

In this research, the linearization scheme of Marino and Mohammadi (1983) is followed. That is, equations (4.4), (4.5), and (4.8) are adopted.

Model Formulation

Figure 2 is a schematic representation of a particular reservoir system. Reservoirs in a system may be located in parallel, e.g. reservoirs A and B, or in series, e.g. reservoirs A and C. Reservoirs A and C are capable of generating hydroelectric power while reservoir B is not. The model formulation in this section is designed to be as general as possible so that it can be applied to any type of system configuration. From this point, j=1,2,...,m and t=1,2,...,T.

The mathematical model of the system is based on continuity equations for reservoir levels. For reservoir j in period t, the continuity equation is written as,

$$S_{j,t} = S_{j,t-1} + I_{j,t} - R_{j,t} - W_{j,t} - G_{j,t} - EV_{j,t} + \sum_{\substack{k=1 \\ k \neq j}}^{m} A_{jk} D_{k,t} \quad (4.9)$$

$$\text{where } A_{jk} = \begin{cases} 1 & \text{if reservoir k releases flows into reservoir j} \\ 0 & \text{otherwise} \end{cases}$$

The system goals and constraints may be expressed either deterministically or probabilistically depending on whether or not the random variable term, $I_{j,t}$ is present. For a constraint, the requirement must be strictly satisfied. For a goal, it is desired to achieve the solution which is as close as possible to the specified target. Thus, meeting the goal requirement is desirable but not strictly required.

The goals and constraints of the system are as follows:

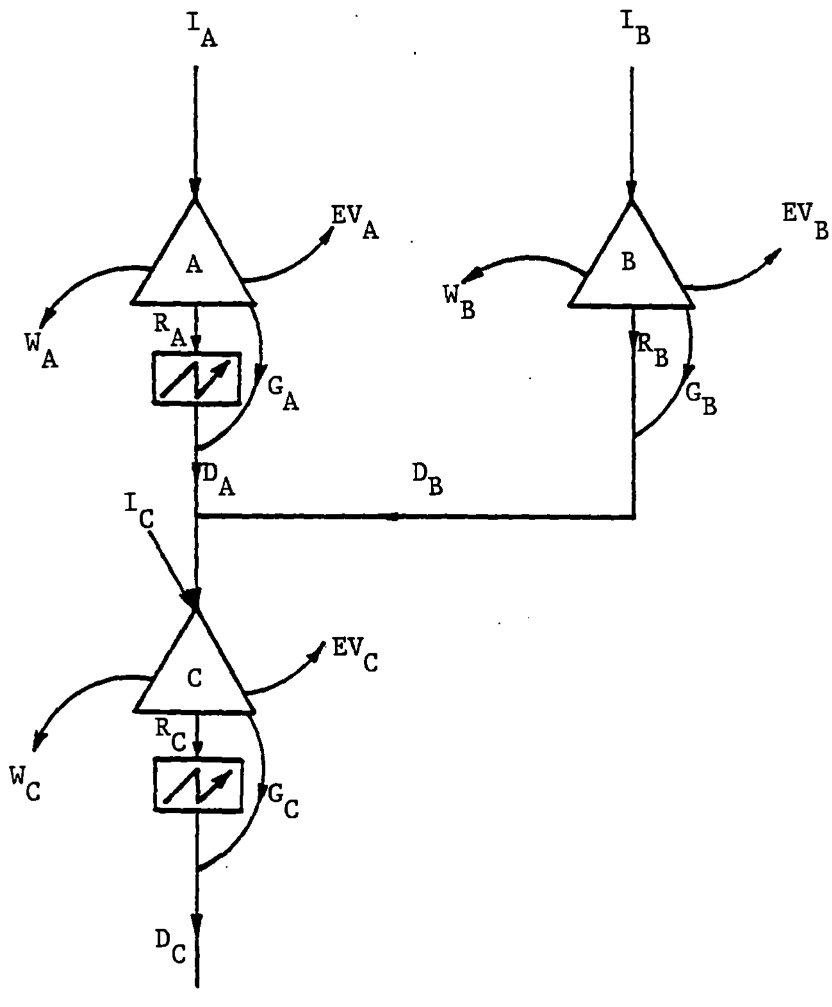

Figure 2. Schematic Representation of a Reservoir System

1) Deterministic goal of meeting the demand for M&I water supply,

$$W_{j,t} \geq MTAR_{j,t} \tag{4.10}$$

2) Deterministic goal of meeting the water demand downstream. This demand usually arises from such purposes as navigation, water quality enhancement, irrigation, and downstream low flow augmentation,

$$D_{j,t} \geq DTAR_{j,t} \tag{4.11}$$

3) Deterministic goal of meeting the demand for hydroelectric power,

$$E_{j,t} \geq PTAR_{j,t}$$

From equation (4.8),

$$R_{j,t}(a_j+b_j S_{j,t-1}) \geq PTAR_{j,t} \tag{4.12}$$

4) For a reservoir with no capability of hydroelectric power generation, the following goal is used in place of (4.11) and (4.12):

$$R_{j,t} \geq DTAR_{j,t} \tag{4.13}$$

5) Probabilistic goal for flood control purpose, i.e. the reservoir storage should not exceed the desired flood protection level,

$$P\{S_{j,t} \leq FC_{j,t}\} \geq \beta_{j,t} \tag{4.14}$$

6) Probabilistic goal for drought control purpose, i.e. the reservoir storage should not be lower than the minimum level for drought protection,

$$P\{S_{j,t} \geq DC_{j,t}\} \geq \gamma_{j,t} \tag{4.15}$$

7) Probabilistic goals for recreational purpose, i.e. the reservoir storage should be maintained between the maximum and minimum desirable levels for recreation,

$$P\{RCMIN_{j,t} \leq S_{j,t} \leq RCMAX_{j,t}\} \geq \eta_{j,t} \tag{4.16}$$

8) Probabilistic constraint of not exceeding the maximum capa-

city of the reservoir,

$$P\{S_{j,t} \le S_{j,max}\} \ge \alpha_{j,t} \tag{4.17}$$

9) Probabilistic constraint of not being lower than the dead storage,

$$P\{S_{j,t} \ge S_{j,min}\} \ge \alpha_{j,t} \tag{4.18}$$

10) Deterministic constraint due to the power plant capacity. Similar to the goal of (4.12), this constraint can be written as,

$$R_{j,t}(a_j+b_j S_{j,t-1}) \le h_t(c_j+d_j S_{j,t-1}) \tag{4.19}$$

11) Deterministic constraint on the relationship among various releases,

$$R_{j,t} + G_{j,t} = D_{j,t} \tag{4.20}$$

12) Deterministic constraint on M&I water release,

$$W_{j,t} \le W_{j,max} \tag{4.21}$$

13) Deterministic constraints on downstream water release,

$$D_{j,min} \le D_{j,t} \le D_{j,max} \tag{4.22}$$

The objective function of this model is to minimize the undesirable deviations, which can be negative and/or positive deviation, from the goals of (4.10)-(4.16). This will be explained later in the chance-constrained goal programming formulation section.

Derivation of the Deterministic Equivalent

In this section, the probabilistic goals and probabilistic constraints are converted to their associated deterministic equivalents. The probabilistic goal of (4.14) is used as an example. From this point, the summation, Σ, stands for $\sum_{k=1,k\neq j}^{m}$, unless specified otherwise. Consider the step by step manipulation of (4.14) below,

$$P\{S_{j,t} \leq FC_{j,t}\} \geq \beta_{j,t} \tag{4.14}$$

Substituting $S_{j,t}$ using the continuity equation of (4.9) yields,

$$P\{S_{j,t-1} + I_{j,t} - R_{j,t} - W_{j,t} - G_{j,t} - EV_{j,t} + \Sigma A_{jk} D_{k,t} \leq FC_{j,t}\} \geq \beta_{j,t}$$

$$P\{I_{j,t} \leq FC_{j,t} - S_{j,t-1} + R_{j,t} + W_{j,t} + G_{j,t} + EV_{j,t} - \Sigma A_{jk} D_{k,t}\} \geq \beta_{j,t} \tag{4.23}$$

Thus, by the definition of a cumulative distribution function (CDF): $F_X(x)=P(X \leq x)$ where X is a random variable, the above goal can be written as,

$$F_{I_{j,t}}(FC_{j,t} - S_{j,t-1} + R_{j,t} + W_{j,t} + G_{j,t} + EV_{j,t} - \Sigma A_{jk} D_{k,t}) \geq \beta_{j,t}$$

Since the inflow is assumed to be normally or lognormally distributed, the inverse of the CDF, $F^{-1}(.)$ is defined. Thus,

$$FC_{j,t} - S_{j,t-1} + R_{j,t} + W_{j,t} + G_{j,t} + EV_{j,t} - \Sigma A_{jk} D_{k,t} \geq F^{-1}_{I_{j,t}}(\beta_{j,t}) \tag{4.24}$$

Note that there is no random variable term in (4.24). This is the reason that (4.24) is regarded as the deterministic equivalent of the probabilistic goal of (4.14).

The other probabilistic goals and constraints in the model can be derived in the same fashion. Their deterministic equivalents will be shown in the section of chance-constrained goal programming formulation.

Derivation of the Conditional CDF

In many studies, the random variables in the model are assumed to be independent. This assumption, however, can lead to less accurate solutions if there exist some correlations among the random variables. With respect to the reservoir operation problem, a realistic approach is to consider a "lag-one" correlation between the current and previous inflows, i.e. the Markov assumption.

In this section, the conditional CDF of the inflow is presented. The procedure is outlined as follows:

1) Determine the probability distribution functions (PDF's) of I_t and I_{t-1}, i.e. $f_{I_t}(i_t)$ and $f_{I_{t-1}}(i_{t-1})$.

2) Determine the joint density function of I_t and I_{t-1}, i.e. $f_{I_t,I_{t-1}}(i_t,i_{t-1})$.

3) Determine the conditional distribution of I_t based on a known value of I_{t-1} from the relationship;

$$f_{I_t|I_{t-1}}(i_t|i_{t-1}) = f_{I_t,I_{t-1}}(i_t,i_{t-1}) / f_{I_{t-1}}(i_{t-1})$$

4) Determine the conditional CDF, $F_{I_t|I_{t-1}}(i_t|i_{t-1})$ from $f_{I_t|I_{t-1}}(i_t|i_{t-1})$.

Two types of probability distribution functions, normal and log-normal, are considered in this study.

Conditional CDF Based on Normal Distribution

Two random variables, X and Y, are normally distributed if their respective PDF's are,

$$f_X(x) = (1/\sqrt{2\pi}\,\sigma_X) \exp[-\tfrac{1}{2}\{(x-\mu_X)/\sigma_X\}^2]$$

$$f_Y(y) = (1/\sqrt{2\pi}\,\sigma_Y) \exp[-\tfrac{1}{2}\{(y-\mu_Y)/\sigma_Y\}^2]$$

where μ_X and μ_Y are the means of X and Y, respectively, and σ_X and σ_Y are the standard deviations of X and Y, respectively.

The joint density of X and Y is called a bivariate normal distribution if its PDF is,

$$f_{X,Y}(x,y) = (1/2\pi\sigma_X\sigma_Y\sqrt{1-\rho^2})\ \exp\ (-a/2)$$

where $a = (1/(1-\rho^2))\,[\{(x-\mu_X)/\sigma_X\}^2+\{(y-\mu_Y)/\sigma_Y\}^2-2\rho(x-\mu_X)(y-\mu_Y)/\sigma_X\sigma_Y]$

and ρ is the correlation coefficient between X and Y.

Thus, the conditional distribution of Y, given X=x is,

$$f_{Y|X}(y|x) = f_{X,Y}(x,y)/\ f_X(x)$$

$$= (1/\sigma_Y\sqrt{2\pi(1-\rho^2)})\exp(-b) \tag{4.25}$$

where $b = [y-\mu_Y-\rho\sigma_Y/\sigma_X(x-\mu_X)]/2\sigma_Y^2(1-\rho^2)$

The conditional distribution of (4.25) is also a normal probability distribution function with mean $\mu_{Y|X}=\mu_Y+\rho(\sigma_Y/\sigma_X)(x-\mu_X)$ and standard deviation $\sigma_{Y|X} = \sigma_Y\sqrt{1-\rho^2}$. Thus, the conditional CDF can be conveniently determined from the standard normal table if $\mu_{Y|X}$ and $\sigma_{Y|X}$ are known.

Conditional CDF Based on Lognormal Distribution

The lognormal distribution is the model for a random variable whose logarithm follows a normal distribution. The lognormal density function of a random variable X is given by,

$$f_X(x) = (1/x\sigma_{\ln(X)}\sqrt{2\pi})\exp[-1/2\sigma^2_{\ln(X)}(\ln(x)-\mu^2_{\ln(X)})]$$

where $\mu_{\ln(X)}$ and $\sigma_{\ln(X)}$ are, respectively, the mean and standard deviation of the logarithm of X.

Since ln(X) is normally distributed, the conditional distribution of ln(X) can be derived in the same fashion as in the case of X itself is normally distributed. The inverse conditional CDF of the random variable can be obtained by taking the exponent of the derived inverse conditional CDF of its logarithm. This may be illustrated by using inequality (4.23) as an example,

$$P\{I_{j,t} \leq FC_{j,t} - S_{j,t-1} + R_{j,t} + W_{j,t} + G_{j,t} + EV_{j,t} - \Sigma A_{jk}D_{k,t}\} \geq \beta_{j,t} \quad (4.23)$$

If $I_{j,t}$ is lognormally distributed, then its logarithm, $\ln(I_{j,t})$, is normally distributed. Taking logarithms of the terms inside the bracket yields,

$$P\{\ln(I_{j,t}) \leq \ln(FC_{j,t} - S_{j,t-1} + R_{j,t} + W_{j,t} + G_{j,t} + EV_{j,t} - \Sigma A_{jk}D_{k,t})\} \geq \beta_{j,t}$$

Thus, the conditional CDF is,

$$F[\ln(FC_{j,t} - S_{j,t-1} + R_{j,t} + W_{j,t} + G_{j,t} + EV_{j,t} - \Sigma A_{jk}D_{k,t})] \geq \beta_{j,t}$$

By the definition of an inverse CDF,

$$\ln(FC_{j,t} - S_{j,t-1} + R_{j,t} + W_{j,t} + G_{j,t} + EV_{j,t} - \Sigma A_{jk}D_{k,t}) \geq F^{-1}(\beta_{j,t})$$

Taking exponents of the above inequality yields,

$$FC_{j,t} - S_{j,t-1} + R_{j,t} + W_{j,t} + G_{j,t} + EV_{j,t} - \Sigma A_{jk}D_{k,t} \geq \exp[F^{-1}(\beta_{j,t})]$$

With the completion of the derivations of deterministic equivalents and conditional CDF, the chance-constrained goal programming can be formulated. This is the topic of the next section.

Chance-Constrained Goal Programming Formulation

In this section, the CCGP formulation of the problem is provided. For notational convenience, F^{-1} is used for the conditional CDF of the random variable (or its logarithm if it is lognormally distributed). The terms $n_{l,j,t}$ and $p_{l,j,t}$ denote, respectively, the positive and negative deviations from goal l of reservoir j during period t. The goals and constraints corresponding to (4.10)-(4.22) are now written as,

1) Deterministic goal of meeting the demand for M&I water supply,

$$W_{j,t} - p_{1,j,t} + n_{1,j,t} = MTAR_{j,t} \tag{4.26}$$

2) Deterministic goal of meeting the water demand downstream,

$$D_{j,t} - p_{2,j,t} + n_{2,j,t} = DTAR_{j,t} \tag{4.27}$$

3) Deterministic goal of meeting the demand for hydroelectric power,

$$R_{j,t}(a_j + b_j S_{j,t-1}) + n_{3,j,t} = PTAR_{j,t} \tag{4.28}$$

4) Deterministic goal corresponding to (4.13),

$$R_{j,t} - p_{2,j,t} + n_{2,j,t} = DTAR_{j,t} \tag{4.29}$$

5) Deterministic equivalent of the probabilistic goal for flood control purpose,

$$F^{-1}(\beta_{j,t}) + S_{j,t-1} - R_{j,t} - W_{j,t} - G_{j,t} - EV_{j,t} + \Sigma A_{jk} D_{k,t} + n_{4,j,t} = FC_{j,t} \tag{4.30}$$

6) Deterministic equivalent of the probabilistic goal for drought control purpose,

$$F^{-1}(1-\gamma_{j,t}) + S_{j,t-1} - R_{j,t} - W_{j,t} - G_{j,t} - EV_{j,t} + \Sigma A_{jk} D_{k,t} - p_{5,j,t} = DC_{j,t} \tag{4.31}$$

7) Deterministic equivalents of the probabilistic goals for recreational purpose,

$$F^{-1}(\eta_{j,t}) + S_{j,t-1} - R_{j,t} - W_{j,t} - G_{j,t} - EV_{j,t} + \Sigma A_{jk} D_{k,t} + n_{6,j,t} = RCMAX_{j,t} \tag{4.32}$$

$$F^{-1}(1-\eta_{j,t}) + S_{j,t-1} - R_{j,t} - W_{j,t} - G_{j,t} - EV_{j,t} + \Sigma A_{jk} D_{k,t} - p_{6,j,t} = RCMIN_{j,t} \tag{4.33}$$

8) Deterministic equivalent of the probabilistic constraint for not exceeding the maximum capacity of the reservoir,

$$F^{-1}(\alpha_{j,t}) + S_{j,t-1} - R_{j,t} - W_{j,t} - G_{j,t} - EV_{j,t} + \Sigma A_{jk} D_{k,t} \le S_{j,max} \tag{4.34}$$

9) Deterministic equivalent of the probabilistic constraint of not being lower than the dead storage of the reservoir,

$$F^{-1}(1-\alpha_{j,t})+S_{j,t-1}-R_{j,t}-W_{j,t}-G_{j,t}-EV_{j,t}+\Sigma A_{jk}D_{k,t} \geq S_{j,min} \quad (4.35)$$

10) Deterministic constraint due to the power plant capacity,

$$R_{j,t}(a_j+b_jS_{j,t-1}) \leq h_t(c_j+d_jS_{j,t-1}) \quad (4.36)$$

11) Deterministic constraint on the relationship among various releases,

$$R_{j,t} + G_{j,t} - D_{j,t} = 0 \quad (4.37)$$

12) Deterministic constraint on M&I water release,

$$W_{j,t} \leq W_{j,max} \quad (4.38)$$

13) Deterministic constraints on downstream water release,

$$D_{j,min} \leq D_{j,t} \leq D_{j,max} \quad (4.39)$$

The goals and constraints of (4.26)-(4.28) and (4.30)-(4.39) are applied for reservoirs which are capable of generating hydroelectric power. For nonpower reservoirs, (4.26), (4.29)-(4.35), and (4.37)-(4.39) are used instead. The objective function of the model is to minimize the positive deviation, or negative deviation, or both from each goal. For example, in order to achieve the target for hydroelectric power generation, $n_{3,j,t}$ is to be minimized. This implies that the underachievement of this goal is not desirable but its overachievement is acceptable. To maximize the amount of hydroelectric power generation which can be greater than the required amount, $PTAR_{j,t}$ should be increased as long as reasonable achievements in lower priority goals are possible. According to the preemptive GP procedure, the user needs to rank various goals with respect to their perceived importance to him. Goals with higher priority are considered before lower priority goals. Thus, the user is assumed to be capable of determining appropriate priority levels among various goals. This approach does not require an explicit weighting factor for each goal which is usually derived from some type of economic analysis.

For the CCGP formulation of the reservoir operation problem in this section, the objective function can be expressed as,

$$\text{Minimize } Z = \sum_{l=1}^{L} P_q \sum_{j=1}^{m} (u_{l,j,t}\, p_{l,j,t} + v_{l,j,t}\, n_{l,j,t}) \qquad q=1,2,\ldots,Q \tag{4.40}$$

As an example, the goals in the model are listed, with the more important goals first, as follows:

1) Water supply for M&I uses
2) Water supply downstream
3) Hydroelectric power generation
4) Recreational purpose
5) Flood control purpose.

The corresponding objective functions for this set of goals is,

$$\text{Minimize } Z = P_1 \sum_{j=1}^{m} n_{1,j,t} + P_2 \sum_{j=1}^{m} n_{2,j,t} + P_3 \sum_{j=1}^{m} n_{3,j,t} + P_4 \sum_{j=1}^{m} (n_{6,j,t} + p_{6,j,t}) + P_5 \sum_{j=1}^{m} n_{4,j,t}$$

Solution Procedures

In this section, the solution procedures for the CCGP formulation of the reservoir operation problem developed in the previous section are presented. The procedural steps are similar to the traditional GP algorithm provided in Lee (1972) or Ignizio (1976). However, the following modifications have been made:

1) In updating the tableau, the revised simplex method is used instead of the simplex method. As indicated by Olson (1984), the revised simplex-based GP tends to have computational advantages over

the full simplex-based GP. This is because unnecessary computations are avoided in the revised simplex method. The description of the revised simplex algorithm is presented in many linear programming books such as Bazaraa and Jarvis (1977).

2) Due to the stochastic nature of the problem, various probabilistic goals and probabilistic constraints need to be converted to their deterministic equivalents. This requires several additional steps to transform the problem into the standard form.

3) The algorithm is designed to be interactive so that the reservoir manager can participate during the session. At each iteration, he can modify the target levels and priority structure according to various goals until a satisfactory solution is obtained.

The time period, t, may be daily, weekly, or monthly depending on available data. This is one advantage of the proposed algorithm since it can be applied to both planning and real-time models. That is, the problem may be solved monthly or weekly for planning purpose and can also be solved daily for the actual operating policy. In both planning and real-time models, the problem is solved according to a specified planning horizon, T. For example, the planning horizons for daily, weekly, or monthly models may be 7 days, 52 weeks, or 12 months, respectively. Due to the uncertainty nature of inflows, only the decision pertaining to the current time period, t, is actually implemented. In the next time period, t+1, the actual value of I_t is realized and the problem is solved again. Similarly, only the decision for period t+1 is adopted. The problem continues this way until the final time period is reached.

The procedural steps to solve the CCGP model are as follows:

Step 1) Identify the time period, t, to be considered.

Step 2) Compute the conditional mean and conditional standard deviation of $I_{j,t}$ based on the known value of $I_{j,t-1}$. Forecasted values are used for unknown values of inflows. For example, $I_{j,t+2}$ is forecasted in order to solve for period t+3 since the actual realization of $I_{j,t+2}$ is not known in the current time period. Any appropriate forecasting techniques, e.g. in Loucks et al. (1981) may be used.

Step 3) Compute the conditional CDF's.

Step 4) Convert various probabilistic goals and probabilistic constraints to their deterministic equivalents.

Step 5) Solve the problem by the revised simplex-based GP algorithm.

Step 6) If the solution obtained is satisfactory, go to step 8.

Step 7) Modify the problem with respect to one or more of the following:

a) target values corresponding to various goals

b) probability levels corresponding to various probabilistic goals

c) priority structure

Return to step 3.

Step 8) If $t > T$, go to step 9. Otherwise $t = t+1$, return to step 2.

Step 9) Stop.

Figure 3 is the flowchart of the solution procedures for the CCGP formulation. The computer program for the algorithm is written in

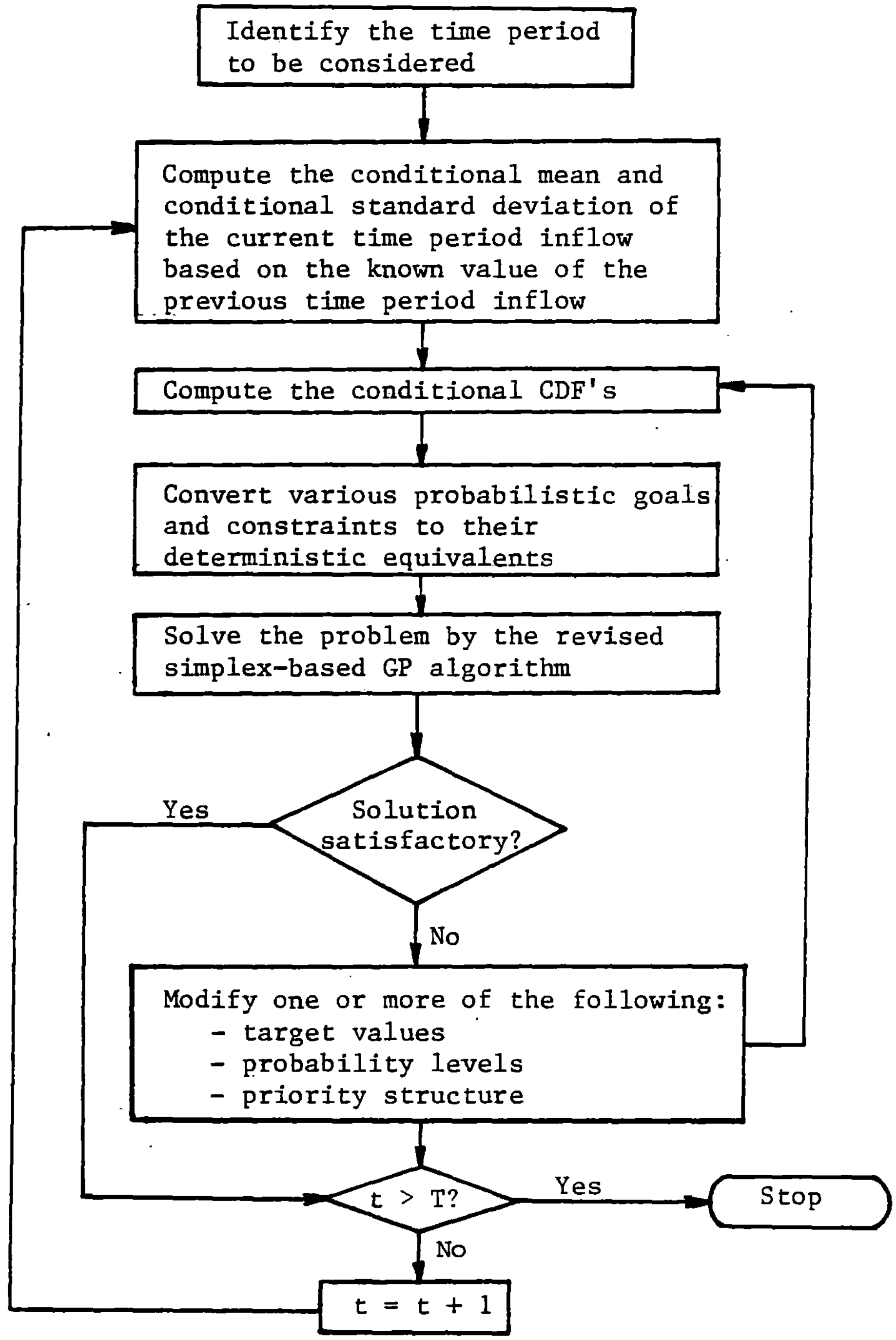

Figure 3. Flowchart of the CCGP Algorithm

FORTRAN 77. The description of the program and its listing are provided in Appendix A and B, respectively.

Summary

This chapter provides the development of the model for a general reservoir system. The CCGP methodology employed in this study is the extension of two popular methodologies in the reservoir operation studies which are CCP and GP. It takes advantage of attractive features in GP and CCP so that systems with multiple objectives and stochastic inflows can be handled. The model formulation is designed to be applicable to any type of system configuration with minor modifications. The inflow into the reservoir is assumed to be either normally or lognormally distributed. Derivations of the deterministic equivalents of various probabilistic goals and constraints in the model have been discussed. The conditional CDF based on the Markov assumption has been considered. The solution procedures for the CCGP formulation have also been outlined.

In Chapter 5, the CCGP methodology will be applied to a real reservoir system and data in order to demonstrate its applicability to real world systems.

CHAPTER V

COMPUTATIONAL EXAMPLE AND ANALYSIS

Introduction

This chapter demonstrates the application of the CCGP methodology developed in Chapter IV to a real multiple-reservoir system. The system chosen is a portion of the Red River reservoir system in Oklahoma. It consists of three multipurpose reservoirs operated by the U.S. Army Corps of Engineers. The description of the system and pertinent data needed in the model are provided in the next two sections. Then, the computation of a conditional CDF is illustrated. The results obtained from an example run are also shown. Finally, a sensitivity analysis of the model is discussed.

Description of the System

The three reservoirs in the system are: Denison, Broken Bow, and Pine Creek. The system configuration is shown in Figure 4. Denison Reservoir is located at mile 725.9 on the Red River, in Bryan County about 5 miles northwest of Denison, Texas. Its purposes are flood control, water supply, hydroelectric power, regulating flows of Red River, improving navigation, and recreation. Broken Bow reservoir is located at mile 20.3 on the Mountain Fork River, a tributary of the Little River in McCurtain County about 9 miles north-northeast of the

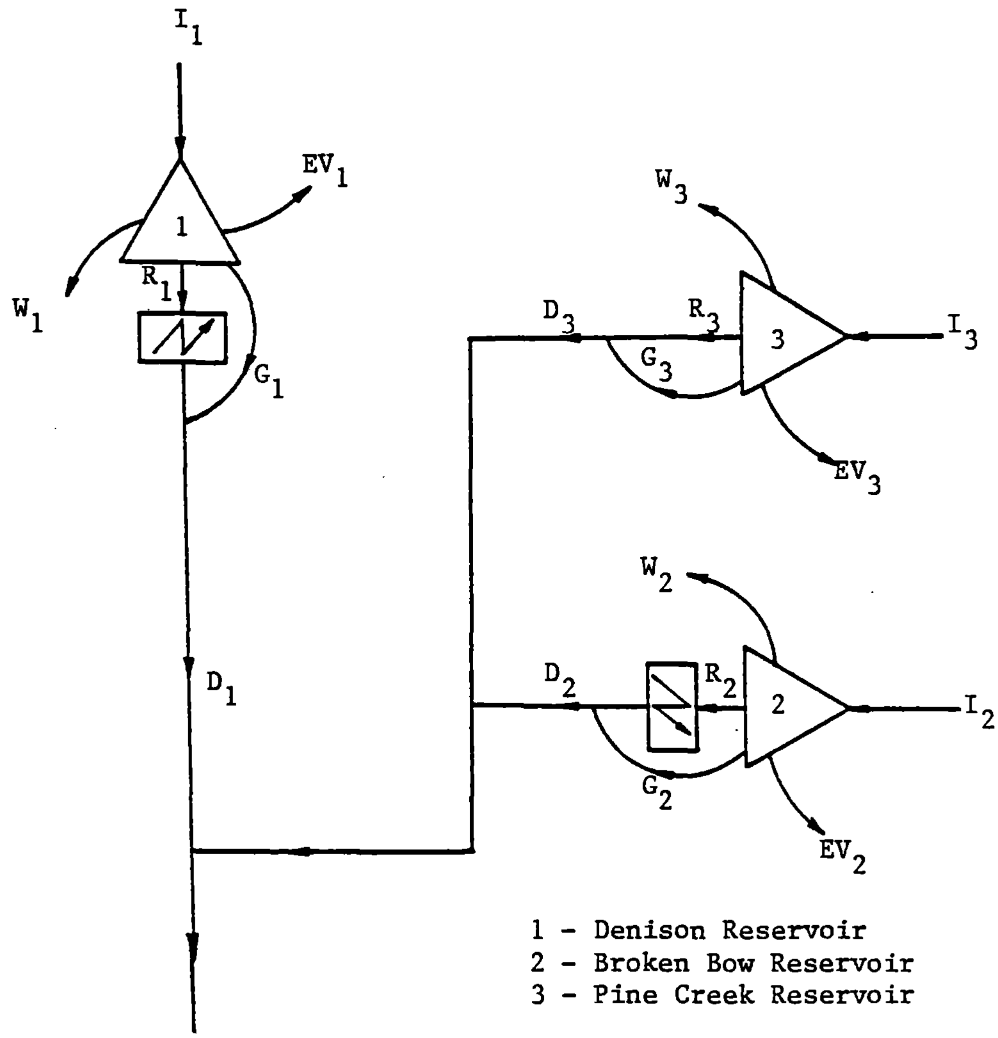

Figure 4. Schematic Representation of the Three-Reservoir System

Town of Broken Bow. Its purposes are flood control, recreation, hydroelectric power, water supply, fish and wildlife protection, and water quality control. Pine Creek reservoir is located on the Little River at mile 145.3, in McCurtain County about 5 miles northwest of Wright City. Its purposes are flood control, water supply, water quality control, fish and wildlife protection, and recreation. The storage data for Denison, Broken Bow, and Pine Creek reservoirs are given in Tables IV, V, and VI, respectively. These tables are adapted from the U.S. Army Corps of Engineers (1970).

TABLE IV

STORAGE DATA FOR DENISON RESERVOIR

Feature	Elevation (NGVD)[1]	Area (Acres)	Capacity (Ac-Ft)[2]
Top of dam	670.0	-	-
Flood control pool	640.0-617.25	143,300	2,637,500
Conservation pool	617.25-590.0	89,625	1,706,200
Inactive & dead pool	Below 590.0	43,890	1,049,200
Total storage			5,392,900

[1]NGVD = National Geodetic Vertical Datum
[2]Ac-Ft = Acre-Feet

TABLE V

STORAGE DATA FOR BROKEN BOW RESERVOIR

Feature	Elevation (NGVD)	Area (Acres)	Capacity (Ac-Ft)
Top of dam	645.0	-	-
Flood control pool	627.5-599.5	17,930	449,800
Conservation pool	599.5-559.0	14,180	469,500
Inactive & dead pool	Below 559.0	9,200	448,700
Total storage			1,368,000

TABLE VI

STORAGE DATA FOR PINE CREEK RESERVOIR

Feature	Elevation (NGVD)	Area (Acres)	Capacity (Ac-Ft)
Top of dam	509.0	-	-
Flood control pool	480.0-443.5	17,200	388,100
Conservation pool	443.5-414.0	4,980	70,500
Inactive & dead pool	Below 414.0	700	7,200
Total storage			465,800

Pertinent Data

The data required in the CCGP model may be classified into three categories: physical data, hydrological data, and demand data. Physical data are data which relate to the constraints of the model, e.g. reservoir and power plant capacities, maximum and minimum flows, storage-elevation-area relationship, flood control storages, etc. Hydrological data include natural inflows into the reservoirs and evaporations from the reservoirs. Demand data involve various demands to be satisfied by the reservoirs such as demand for M&I water supply, demand for hydroelectric power generation, and desired storage levels for recreational purpose. Some of the data can be found in the U.S. Army Corps of Engineers (1970). The data which involve hydroelectric power generation are supplied by Southwestern Power Administration in Tulsa, Oklahoma. For those data which are not available, estimations are made with the help from the staff of the U.S. Army Corps of Engineers, Tulsa District. The data in each category and their sources are provided next.

Physical Data

The necessary data for each reservoir in this category are as follows:

1) The reservoir maximum capacity and dead storage.

2) The maximum allowable release for M&I water supply.

3) The maximum allowable and minimum required releases for downstream water supply.

4) The relationships between reservoir storage and elevation, surface area, energy rate, and power plant capacity.

5) The number of hours used to operate the reservoir.

These data are given in Tables XIII-XX in Appendix C.

In order to express the rate of energy production (ξ) and the power plant capacity (PMAX) as linear functions of the reservoir storage (S) as in the forms of equations (4.4) and (4.5), respectively, regression analyses of S against ξ, and S against PMAX are carried out with the data from Tables XVI-XVIII. The regression analysis of the reservoir surface area against storage is also performed. Results for these are as follows:

a) For Denison reservoir,

$$\underset{(\text{KWHr/KAc-Ft})}{\xi} = 66694.0497 + (8.0175 \times 10^{-3})S$$

The correlation coefficient is 0.9636.

$$\underset{(\text{KW})}{\text{PMAX}} = \begin{cases} 32859.7038 + (22.4448 \times 10^{-3})S & , \ S \leq 2105300 \text{ Ac-Ft} \\ 80500 & , \text{ Otherwise} \end{cases}$$

The correlation coefficient for the first segment is 0.9942.

$$\underset{(\text{Acres})}{\text{AREA}} = 25602.6457 + (21.6949 \times 10^{-3})S$$

The correlation coefficient is 0.9845.

b) For Broken Bow reservoir,

$$\underset{(KWHr/KAc\text{-}Ft)}{\xi} = 103451.3762 + (64.0659 \times 10^{-3})S$$

The correlation coefficient is 0.9902

$$PMAX = \begin{cases} 36671.8054 + (89.0432 \times 10^{-3})S & , \quad S \leq 925180 \text{ Ac-Ft} \\ 115000 & , \text{ Otherwise} \end{cases}$$

The correlation coefficient for the first segment is 0.9938.

$$\underset{(Acres)}{AREA} = 5287.8060 + (9.4670 \times 10^{-3})S$$

The correlation coefficient is 0.9947.

c) For Pine Creek reservoir there is no capability for hydroelectric power generation. Thus, only the regression analysis of AREA against S is performed.

$$\underset{(Acres)}{AREA} = 1929.1776 + (0.0352)S$$

The correlation coefficient is 0.9536.

Summary of the regression analysis results is given in Table XIX in Appendix C. Figures 14-20 are also provided in Appendix C to show the linear approximations of actual curves.

Hydrological Data

This group of data includes the natural inflow into the reservoir and the net evaporation. Both of these can be found in the U.S. Army Corps of Engineers (1970) for water years 1923 to 1967. The historical inflow data are then used to determine the distribution which is the best fit for all months. With the Kolmogorov-Smirnov goodness-of-fit test (Phillip,1972), the lognormal distribution fits very well with the historical inflow data. At a significant level of 0.05, there is not sufficient evidence to reject the null hypothesis that the inflow of a particular month is lognormally distributed since the type I error is at least 0.20. This applies for all the three reservoirs, and in most cases type I errors are much higher than 0.20. Thus, the conditional CDF of the inflow to be considered later for this system will be based on the lognormal distribution of each individual monthly inflow. Tables XXI-XXIII in Appendix C provide the historical inflow data for the three reservoirs. The average monthly evaporations (Ft) are also shown in Table XXIV in Appendix C. The monthly net evaporation (Ac-Ft) from each reservoir can be obtained by multiplying the average monthly evaporation with the surface area. The surface area can be determined from the regression analysis explained earlier.

Demand Data

For each reservoir, the following monthly demand data are required:

1) Monthly demand for M&I water supply
2) Monthly demand for downstream water supply
3) Monthly demand for hydroelectric power generation
4) Monthly flood protection level
5) Monthly desired reservoir levels for recreational purpose.

The first three demand data are normally obtained from contract requirements with other private and public agencies. The demand in each of the three cases may be considered as the required amount to be fulfilled as much as possible. Thus, negative deviation from the required amount is undesirable while positive deviation is acceptable or, in some situations, beneficial. For example, attempts are usually made to maximize the hydroelectric power generation, as long as the other purposes are not negatively affected and the power plant capacity is not exceeded, since the additional hydroelectric power can always be sold, although at a price cheaper than the required amount. The monthly demand data for the first three purposes are given in Tables XXV-XXVI in Appendix C. During high runoff periods, flood protection is usually given the highest priority. The goal for flood protection is to keep the reservoir level below the specified flood protection level. If the reservoir level rises above the flood control level, attempts are usually made to release as much as possible provided that the downstream channel capacity is not exceeded. The monthly flood protection level may be constant throughout the year, as in Denison and Broken Bow reservoirs, or may be varied from month to month, as in Pine Creek reservoir. These data are given in Table XXVII in Appendix C. Although recreation was not explicitly considered to be among the major purposes of many reservoirs in the past, there has long been evidence that most reservoirs are valuable and popular resorts for recreational purpose. In order to play a "good guy" role, the U.S. Army Corps of Engineers has directed considerable attention to this purpose. Several studies performed have been related to the desirable reservoir level for recreation, e.g. Badger and Wolff (1972). The general guideline is to keep the reservoir level around the top of the reservoir conservation pool. The purpose definitely results in the reduction of potential hydroelectric power which can be generated. However, as long as the required amount of hydroelectric power can be satisfied, the gains from recreational purpose, which are normally difficult to measure in the economical sense, may well be justified for the sacrifice of noncritical hydroelectric power in the social well being sense. The desirable storage levels for Denison, Broken Bow, and Pine Creek reservoirs are provided in Table XXVIII in Appendix C.

Computation of the Conditional CDF

In this section, an example is provided to illustrate the computation of a conditional CDF. The inflow into Denison reservoir during the month of February is chosen as the example. Thus, time periods t-1 and t correspond to January and February, respectively. According to the procedure in deriving the conditional CDF explained in Chapter IV, the outlined steps are carried out as follows:

1) The lognormal distribution tends to be a very appropriate distribution for both I_{t-1} and I_t. Using the data in Table XXI for the months of January and February, the mean and standard deviation for the logarithm of I_{t-1} are, respectively, 7.2167 and 0.8290, and for I_t they are 7.5916 and 1.0462. The correlation coefficient (ρ) between the two months is found to be 0.6371.

2) The conditional mean and conditional standard deviation of the logarithm of February inflow based on a known value of January inflow are,

$$\mu_{\ln(I_t)|\ln(I_{t-1})} = \mu_{\ln(I_t)} + \rho(\sigma_{\ln(I_t)}/\sigma_{\ln(I_{t-1})})(\ln(I_t) - \mu_{\ln(I_t)})$$

$$\sigma_{\ln(I_t)|\ln(I_{t-1})} = \sigma_{\ln(I_t)}(1-\rho^2)^{\frac{1}{2}}$$

Assume that the inflow for January was realized to be 2000 cfs, then the conditional mean and conditional standard deviation according to the above equations are 7.8666 and 0.7884, respectively.

3) The conditional CDF can be computed by means of the standard normal table with the conditional mean and conditional standard de-

viation instead of their corresponding nonconditional parameters.

Table VII shows the nonconditional CDF of February and the conditional CDF of February based on the 2000 cfs inflow in January. The other conditional CDF's based on other values of January inflows can be computed in the same manner. Figure 5 shows the curves of the nonconditional CDF and conditional CDF's of February based on 400, 800, 2000, and 5000 cfs of January inflows. The difference among the curves is significant, this shows that the use of nonconditional CDF, as in most studies, tends to underestimate the curve if the previous period inflow was high while it tends to overestimate the curve in case of low inflow of the previous period. Thus, in situations where the correlation between successive periods cannot be neglected, the use of conditional CDF's is likely to improve the accuracy of the results since the actual value of the previous period inflow is explicitly considered.

Computational Experience

The release decisions from the three-reservoir system are determined by the proposed CCGP methodologies during the years 1977-1980. The planning horizon is chosen to be 12 months. For each run, only the release decision according to the current time period, t, is actually used. At the end of period t, the actual value of I_t is known and the problem is solved again for time periods t+1, t+2, ..., t+12. Similarly, only the release decision of time period t+1 is implemented. This process continues until the final time period is reached. The forecast of inflows for all the three reservoirs is identified to be ARIMA $(1,0,1)_{12}x(1,0,1)$. The results for the years 1977-1980 obtained from the proposed methodology is satisfactory with respect to the

TABLE VII

NONCONDITIONAL CDF AND CONDITIONAL CDF
OF FEBRUARY INFLOW BASED ON A KNOWN
VALUE OF JANUARY INFLOW (2000 CFS)

February Inflow (I_t)[1]	Logarithm of February Inflow ($\ln(I_t)$)	Nonconditional CDF	Conditional CDF[2]
254	5.537	0.022	0.002
292	5.677	0.031	0.003
411	6.019	0.062	0.010
493	6.201	0.087	0.017
501	6.217	0.089	0.018
554	6.317	0.106	0.025
706	6.560	0.156	0.049
745	6.613	0.169	0.056
810	6.697	0.191	0.069
811	6.698	0.191	0.069
871	6.770	0.211	0.082
1019	6.927	0.258	0.117
1058	6.964	0.270	0.126
1098	7.001	0.282	0.136
1136	7.035	0.293	0.146
1279	7.154	0.334	0.183
1304	7.173	0.341	0.190
1345	7.204	0.352	0.200
1541	7.340	0.403	0.252
1572	7.360	0.410	0.260
1629	7.396	0.424	0.275
1672	7.422	0.434	0.286
1719	7.449	0.445	0.298
1755	7.470	0.453	0.308
2227	7.708	0.545	0.420
2436	7.798	0.580	0.465
2443	7.801	0.581	0.467
2691	7.898	0.618	0.516
2769	7.926	0.628	0.530
2914	7.977	0.647	0.556
3911	8.272	0.747	0.696
3928	8.276	0.748	0.698
4139	8.328	0.764	0.721
4435	8.397	0.785	0.750
4651	8.445	0.798	0.768
4735	8.463	0.803	0.775
5028	8.523	0.819	0.797
5484	8.610	0.840	0.827
7029	8.858	0.892	0.896
7134	8.873	0.895	0.899
7159	8.876	0.895	0.900
7676	8.946	0.907	0.914
9595	9.169	0.938	0.951
12031	9.395	0.961	0.974
19628	9.885	0.988	0.995

[1]From the data in Table XXI, Appendix C. The February inflows from years 1923-1967 are rearranged in increasing order.

[2]With January inflow of 2000 cfs, the conditional mean and conditional standard deviation are 7.8666 and 0.7884, respectively.

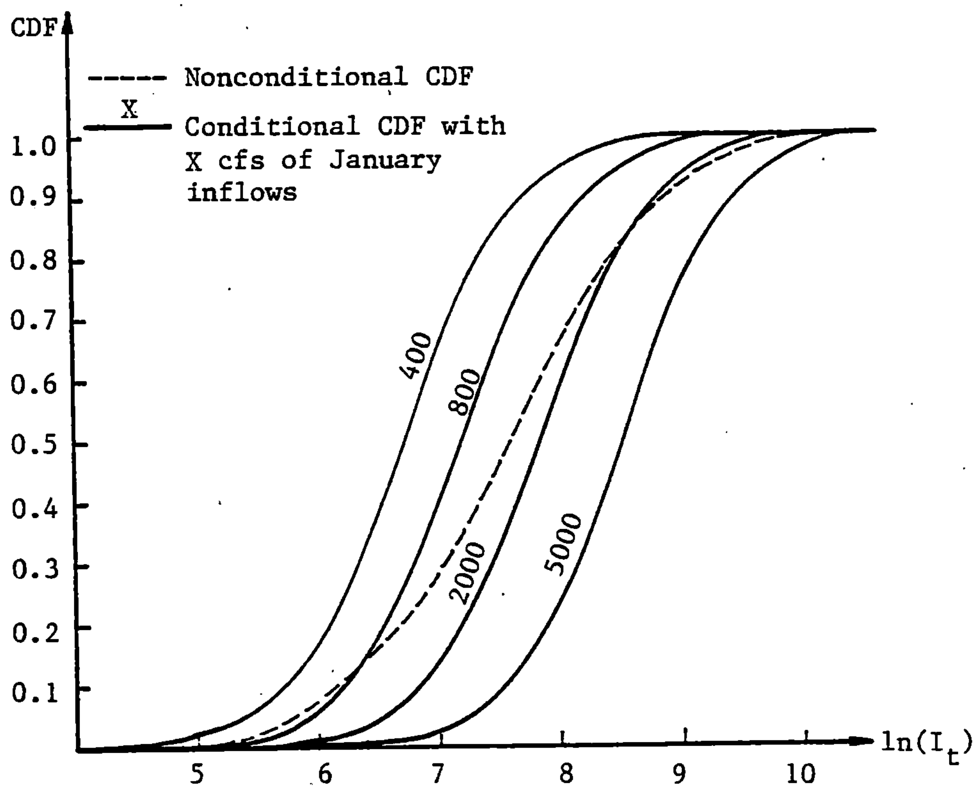

Figure 5. Plots of Conditional and Nonconditional CDF's of February Inflows Based on Known Values of January Inflows

criteria of required releases and storage boundaries. That is, the reservoir storages in all three reservoirs are always within their maximum and minimum allowable storage levels, and the required amount of monthly releases for M&I water supply, downstream flow, and hydroelectric power generation are always satisfied. As an example, the computational experience with the year 1980 is discussed.

The priority structure, with the highest priority goal being listed first, is chosen to be:

1) Water supply for M&I
2) Water supply downstream
3) Hydroelectric power generation
4) Recreation
5) Flood control.

The probability levels in various probabilistic goals and probabilistic constraints: $\alpha_{j,t}$, $\beta_{j,t}$, $\gamma_{j,t}$, and $\eta_{j,t}$ are chosen to be 0.90.

Table VIII shows the desired releases which should be made according to the five goals. For the goals of M&I water supply, downstream water supply, hydroelectric power generation, and flood control, it is desirable to avoid underachievements of target values. For recreational purpose, releases should not be made more than specified. The amount of releases corresponding to recreational and flood control purposes, e.g. 0 and 781 in February from Denison, are dependent on the probability levels. For example, to be 90% confident that the reservoir storage level does not exceed the flood control level in March, at least 781 ac-ft should be released in February from Denison reservoir. However, with respect to recreational purpose, no release should be made from Denison reservoir during the month of February in order to be

TABLE VIII

DESIRED MONTHLY RELEASES FOR VARIOUS GOALS (AC-FT)

	Denison					Broken Bow					Pine Creek			
Month	M&I (≥)	D (≥)	P (≥)	R (≤)	FC (≥)	M&I (≥)	D (≥)	P (≥)	R (≤)	FC (≥)	M&I (≥)	D (≥)	R (≤)	FC (≥)
January	2762	0	116844	17546	0	5985	10128	33848	0	115882	7734	3314	6539	121312
February	2762	0	93741	0	781	5985	10128	28797	0	228270	7734	3314	26598	106679
March	2762	0	105195	4702	32153	5985	10128	27941	94323	247572	7734	3314	54040	112711
April	2762	0	105306	0	228686	5985	10128	29069	55998	205974	7734	3314	2330	60746
May	2762	0	132379	0	950540	5985	10128	35644	11421	198300	7734	3314	40846	151366
June	2762	0	149895	0	0	5985	10128	41367	0	65422	7734	3314	56520	75889
July	2762	0	160890	165466	475644	5985	10128	43287	63192	132153	7734	3314	39834	46054
August	2762	0	158569	103900	60889	5985	10128	42351	74961	181153	7734	3314	1615	0
September	2762	0	126813	44253	724474	5985	10128	35409	35275	95550	7734	3314	0	5569
October	2762	0	110931	0	387737	5985	10128	29728	37655	319173	7734	3314	0	0
November	2762	0	104063	0	0	5985	10128	28829	16960	133790	7734	3314	64906	225221
December	2762	0	112989	0	0	5985	10128	30182	13887	130156	7734	3314	15331	71917

M&I – Municipal and Industrial Water Supply
D – Downstream Water Supply
P – Hydroelectric Power Generation
R – Recreation
FC – Flood Control

90% confident that the storage level is not lower than the desired recreational level. In most of the months, the desired minimum release for flood control and maximum release for recreation are conflicting.

Table IX shows various releases and amount of hydroelectric power generated in each month. These releases are identified by the CCGP methodology. In all 12 months, the first three goals corresponding to water supply for M&I, water supply downstream, and hydroelectric power generation are satisfied. The monthly targets for hydroelectric power generation from Denison reservoir are reasonably high and attempts to increase these targets will have negative effect on recreational purpose. However, the amount of hydroelectric power generated from Broken Bow reservoir can be increased in many months without degrading the achievement in recreational goal. This can be achieved by releasing water for M&I use only as much as required and releasing all other water through the turbine. For example, only 5985 instead of 66382 ac-ft should be released for M&I use during the month of March. Thus, both underachievement and overachievement of the M&I water supply goal are undesirable. The new scheduled release from Broken Bow reservoir with this modification is shown in Table X. The yearly increase in the amount of hydroelectric power generated from Broken Bow reservoir is 26302 MWH. In most of the months, the goals of recreation and flood control are not totally satisfied since releases are normally made more than specified by recreational goal and less than specified by flood control purpose. During high runoff periods, the reservoir manager may want to release more to prevent possible flooding, while during recreational months he may want to release less. This can be done through the interactive decision making described earlier.

TABLE IX

MONTHLY RELEASES FOR VARIOUS GOALS (AC-FT)

Month	Denison M&I (W_{1t})	Denison Power (R_{1t})	Denison Total	Broken Bow M&I (W_{2t})	Broken Bow Power (R_{2t})	Broken Bow Total	Pine Creek M&I (W_{3t})	Pine Creek Downstream (D_{3t})	Pine Creek Total
January	2762	116844	119606	5985	33848	39833	7734	3868	11602
February	2762	93741	96503	5985	28797	34782	22730	3868	26598
March	2762	105195	107957	66382	27941	94323	50172	3868	54040
April	2762	105306	108068	26929	29069	55998	7734	3868	11602
May	2762	132379	135141	5985	35644	41629	36978	3868	40846
June	2762	149895	152657	5985	41367	47352	52652	3868	56520
July	2762	162704	165466	19906	43287	63193	35966	3868	39834
August	2762	158569	161331	32611	42351	74962	7734	3868	11602
September	2762	126813	129575	5985	35409	41394	7734	3868	11602
October	2762	110931	113693	7927	29728	37655	7734	3868	11602
November	2762	104063	106825	5985	28829	34814	61038	3868	64906
December	2762	112989	115751	5985	30182	36167	11463	3868	15331

TABLE X

MONTHLY RELEASES FROM BROKEN BOW RESERVOIR
WITH HIGHER AMOUNT OF HYDROELECTRIC POWER

Month	M&I Release (Ac-Ft)	Power Release (Ac-Ft)	Total (Ac-Ft)	Power Generated (MWH)	Power Demand (MWH)	Surplus Power (MWH)
January	5985	33848	39833	5943	5050	893
February	5985	28797	34782	4480	4480	0
March	5985	88338	94323	14354	4540	9814
April	5985	50013	55998	8035	4670	3365
May	5985	35644	41629	5640	5640	0
June	5985	41367	47352	6560	6560	0
July	5985	57208	63193	9344	7070	2274
August	5985	101588	74962	16592	6950	9642
September	5985	35409	41394	5720	5720	0
October	5985	31670	37655	5114	4800	314
November	5985	28829	34814	4610	4610	0
December	5985	30182	36167	4800	4800	0
					TOTAL =	26302

The reservoir storages according to the release decision in Table IX together with actual inflows and actual storages for the year 1980 are given in Table XI. From this table, plots of actual and projected storages during the year 1980 can be made for comparison. Similar analysis can be carried out for other years. Based on the years 1977-1980, the actual and projected storages for the three reservoirs are plotted in Figures 6-8.

For Denison and Broken Bow reservoirs, the results are generally satisfactory with respect to all goals. The requirements for M&I and downstream water supply are met. Denison reservoir can generate hydroelectric power according to the monthly demand. Broken Bow reservoir can generate more power than the specified targets in many months when additional release can be made without degrading the recreational goal. Both reservoir storage levels are reasonably high between the months of May - September during which recreational visits to the reservoirs are high. In some months, the projected reservoir storages exceed their flood control levels. The reason for this is that recreation is given higher priority than flood control. Thus, to guard against the possibility of low runoffs during the next period, releases from the reservoirs during the current period are limited by the recreational goal. In order to lower the projected storage levels in some months, the reservoir manager can increase the power demands or switch the priority levels between recreation and flood control. From Figures 6 and 7, the actual and projected storages seem to follow similar trends in both reservoirs.

TABLE XI

RESERVOIR STORAGES AND INFLOWS (AC-FT)

	Denison			Broken Bow			Pine Creek		
Month	Actual Inflow	Actual Storage	Projected Storage*	Actual Inflow	Actual Storage	Projected Storage*	Actual Inflow	Actual Storage	Projected Storage*
January	80034	2380000	2216139	132310	860000	813543	22074	77000	57755
February	115678	2320000	2228033	134990	811500	921487	49067	76700	81448
March	58672	2271000	2169392	61509	791400	892854	5738	77850	33603
April	56708	2241000	2097677	17444	860600	855064	42861	86620	65577
May	73251	2662000	2012886	45206	945300	860500	75065	103100	100984
June	586541	2680000	242160	116577	868400	934646	42100	80370	87166
July	167090	2494000	2384173	75134	797600	946759	3045	72310	49123
August	145252	2296000	2324807	37168	744900	906712	2693	64620	39221
September	96398	2312000	2249037	41956	779900	905507	1932	126900	28364
October	33858	2367000	2140452	14422	798700	881197	89410	78450	106980
November	37488	2334000	2054053	20636	795900	867605	11476	78550	53113
December	33858	2399000	1960217	26337	848400	859661	46198	79350	84882

*According to the scheduled release identified by the CCGP methodology.

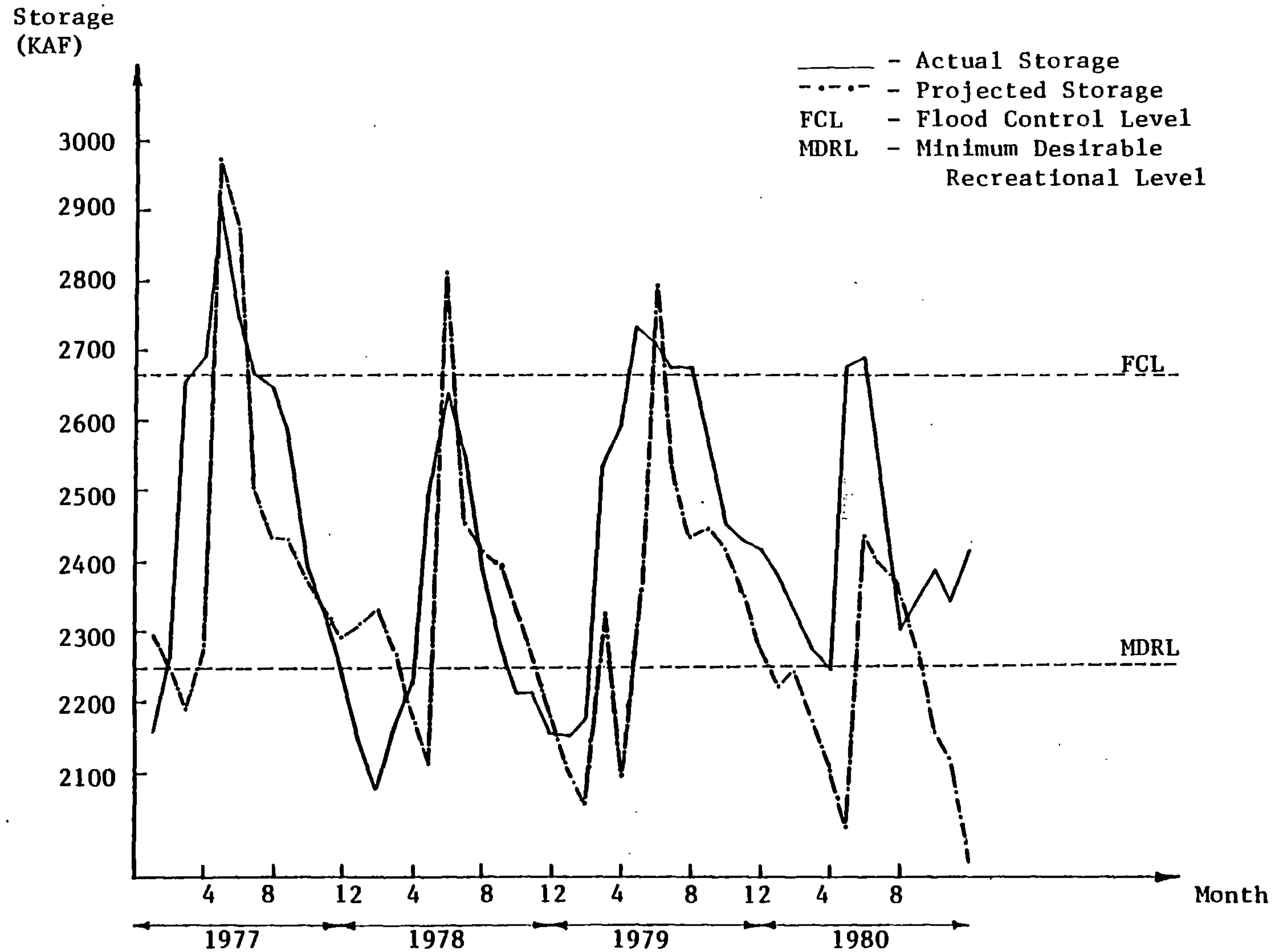

Figure 6. Plots of Actual and Projected Storages for Denison Reservoir from 1977-1980

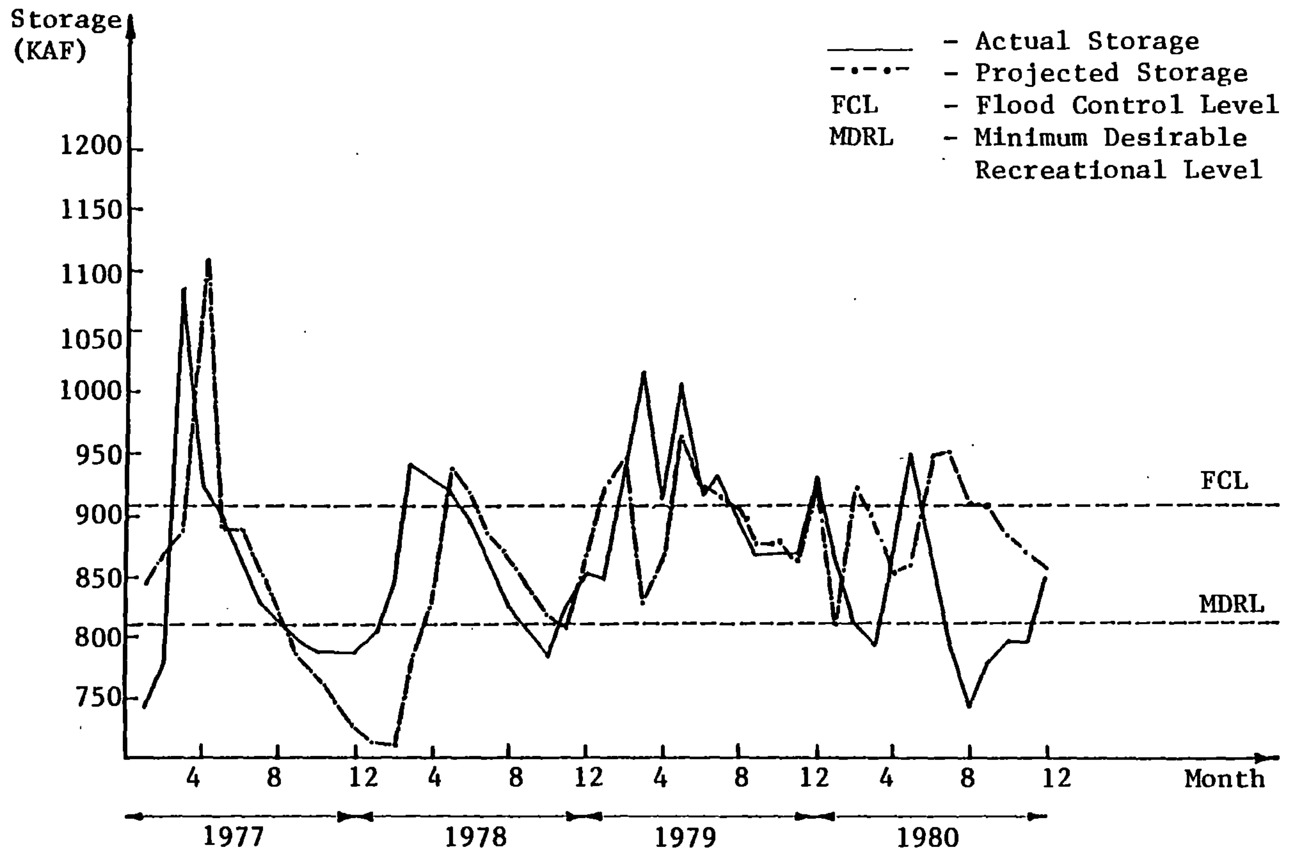

Figure 7. Plots of Actual and Projected Storages for Broken Bow Reservoir from 1977-1980

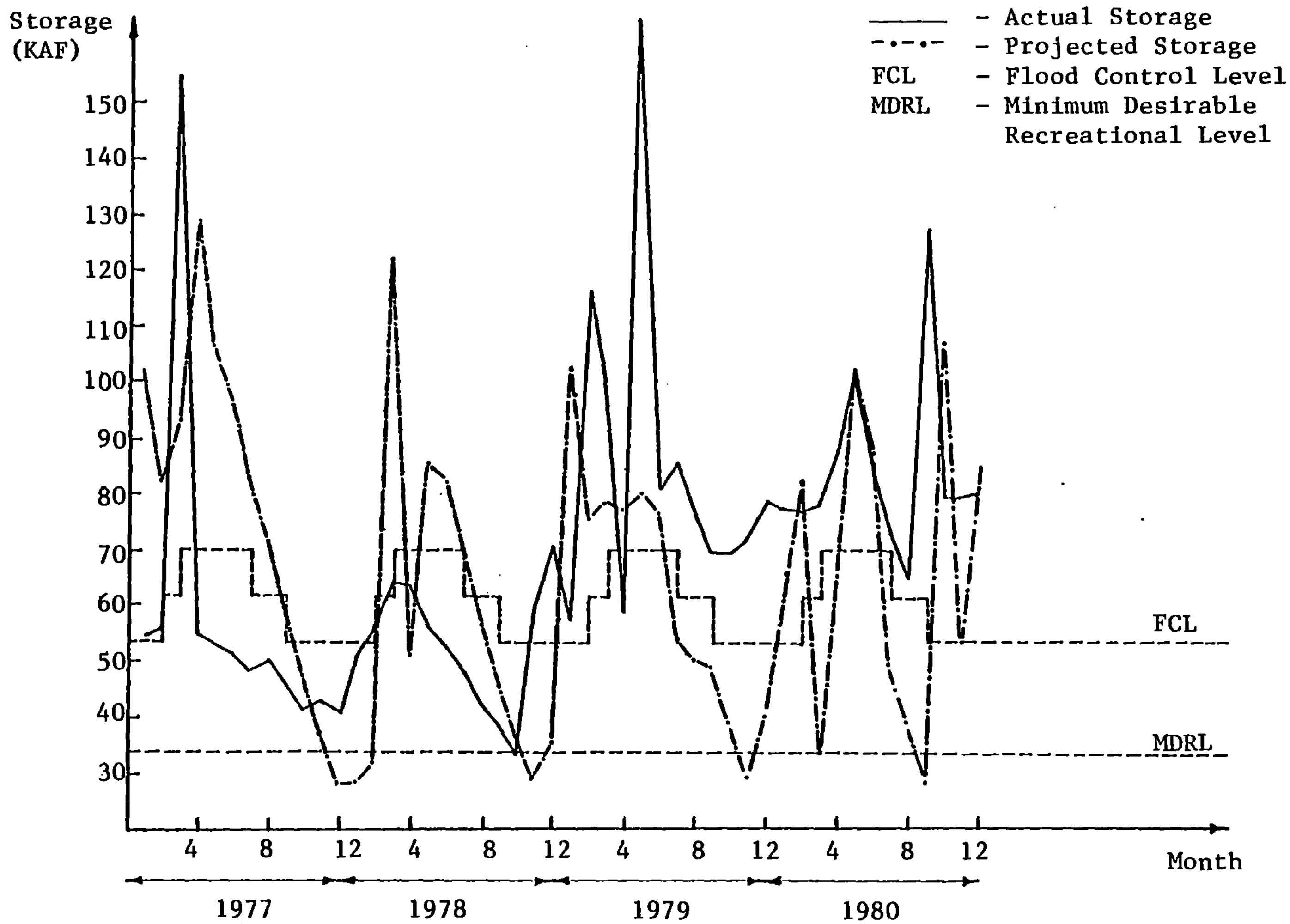

Figure 8. Plots of Actual and Projected Storages for Pine Creek Reservoir from 1977-1980

Figure 8 shows that both lines of actual and projected storages for Pine Creek reservoir exhibit high degrees of fluctuations. There are two reasons for this: first, the shape of this reservoir is steeper than the other two reservoirs; second, the variation in the monthly inflow into this reservoir has much greater impact on the storage level since the magnitude of the inflow can be as large as the reservoir storage. The average magnitudes of inflows for Denison, Broken Bow, and Pine Creek are respectively about 10%, 15%, and 100% of the reservoir conservation storages (i.e. storages below flood control levels). Thus, the flood control level for Pine Creek reservoir can be exceeded easily during a high runoff period even though the storage level at the beginning of the period is kept as low as the inactive storage level. Inflows into this reservoir tend to be extremely low during the last four to five months of the year. Thus, to be able to satisfy the goals of M&I and downstream water supply, the reservoir storage should be kept considerably higher than the flood control level prior to these periods. From Figure 8, the actual storage tends to fluctuate above the flood control level while the projected storage tends to fluctuate between the flood control and minimum desirable recreational levels. The projected storages during recreational months seem to be reasonably high.

Sensitivity Analysis

In this section, sensitivity analysis of the CCGP model for the reservoir operation problem is discussed. Three factors which have important effects on the result are priority structure, target values, and probability levels. Discussions will be made with respect to both the general case and the three-reservoir system analyzed in this chapter. Results from Denison reservoir will be provided as the examples.

Priority Structure

Different priority structures can result in large differences in release decisions. Assigning priorities to various goals in the model depends heavily on the reservoir manager's judgement. During high runoff periods, flood control tends to be the major concern since other goals can be fulfilled. However, keeping the reservoir storage below the flood control level at all time can lead to large degradations in other goals when inflows are low during some successive periods. Guidelines in arranging priority levels and their effects are as follows:

1) The releases required from the goals of M&I and downstream water supply are generally small compared with other goals. However, it is important that these requirements are satisfied. Thus, high priorities are usually given to these goals. For, M&I water supply, the release target should be met exactly if the reservoir is also used for hydroelectric power generation. This is because excess amount of water should be released through the turbine so that additional amount of power can be produced.

2) The primary concern for hydroelectric power generation purpose is to be able to meet the contracted amount. If additional power can be generated without degrading lower priority goals, then it is highly desirable to do so. This goal is usually ranked high on the priority list. As evidence in Figures 6 and 7, fluctuations in the storage level should be expected if this goal is given high priority. The reason for this is that power targets can be easily satisfied during high inflow periods and the storage level can be kept above the

minimum desirable recreational level. However, during low inflow periods it is necessary to draw water from the reservoir to generate enough power.

3) If recreation is ranked higher than flood control and power generation, the reservoir storage will tend to be stable around the desirable recreational level. The amount of power generated is likely to be greatly reduced during low inflow months due to the need to keep the reservoir level relatively high. Figure 9 shows plots of projected storage level for Denison reservoir with recreation ranked higher than power generation and flood control. The scheduled release and amount of hydroelectric power generated during the years 1977-1980 are provided in Table XII. From this table, it can be seen that the power generated is far less than the target amount in many months. However, during a few months when inflows are very high the amount generated is much greater than the targets.

4) Large degrees of fluctuations in the storage level should be expected if flood control is considered as the highest priority. In order to keep the storage below the flood control level, large amount of releases need to be made during high inflow periods. Although releases are not required by this goal during low inflow periods, water is usually drawn from the reservoir to serve other purposes. Examples of this case are provided in Figure 10.

Target Value

Target values of various goals are parameters which also have great impact on the results. With the types of goals considered in this model, there is no release decision which completely satisfies all the goals simultaneously. During high inflow periods, recreation tends

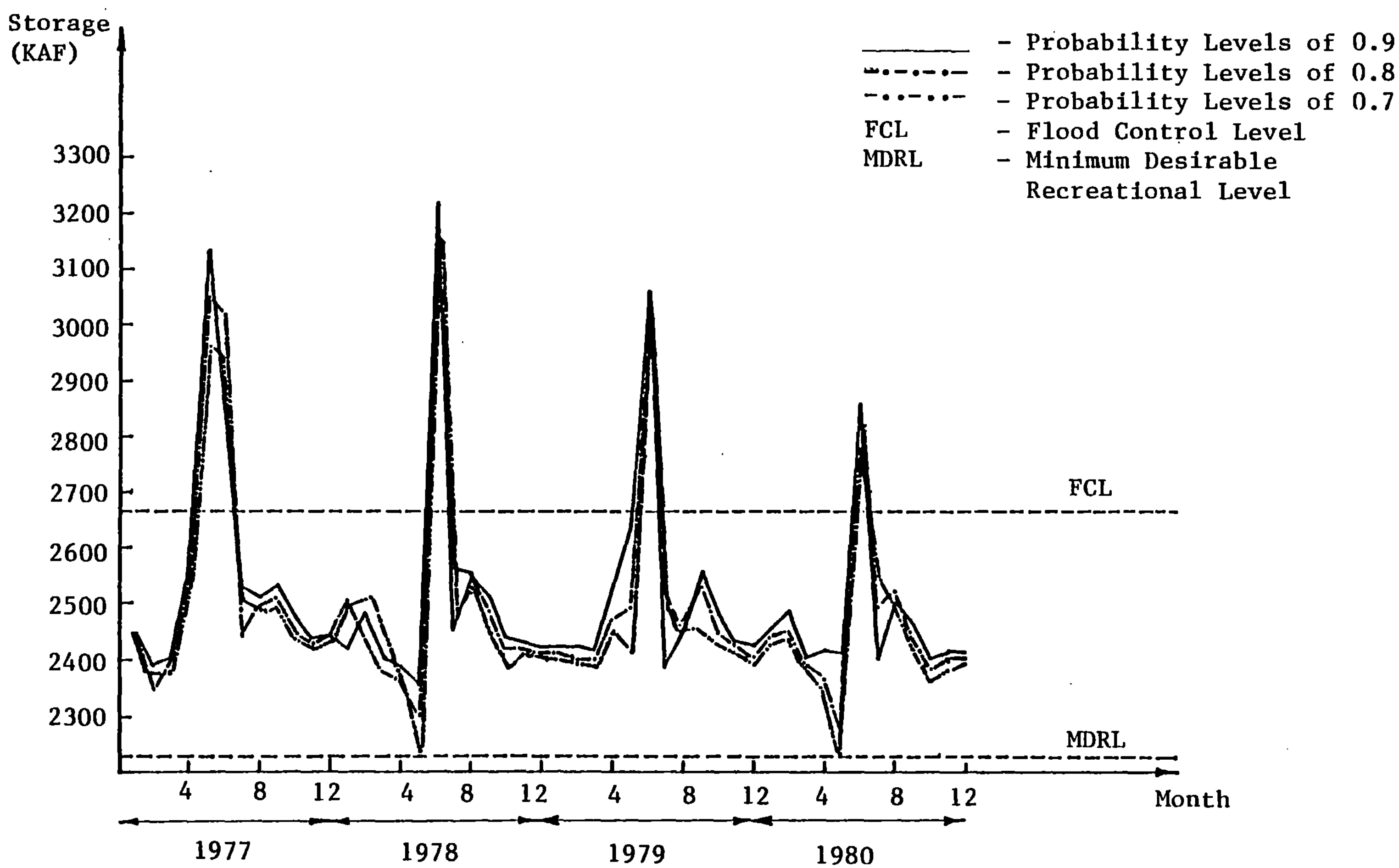

Figure 9. Projected Storage of Denison Reservoir With Priority Structure: M&I, D, R, P, FC

TABLE XII

1977–1980 RELEASE DECISION AND AMOUNT OF MONTHLY HYDROELECTRIC POWER GENERATED FROM DENISON RESERVOIR*

Month	Power Target (MWH)	1977 Release Decision (Ac-Ft)	1977 Power Generated (MWH)	1978 Release Decision (Ac-Ft)	1978 Power Generated (MWH)	1979 Release Decision (Ac-Ft)	1979 Power Generated (MWH)	1980 Release Decision (Ac-Ft)	1980 Power Generated (MWH)
January	10040	7225	378	73405	6101	47971	3896	80178	6667
February	8020	75526	6257	54144	4427	54805	4484	138235	11739
March	9010	20860	1563	128097	10858	40300	3231	27618	2136
April	8970	42019	3377	38002	3029	182968	15671	57051	4675
May	11200	281717	24330	86890	7224	362304	31570	119717	10067
June	12580	883536	80796	7225	382	811714	73780	588870	52527
July	14030	454643	40455	828177	76330	7225	383	7225	384
August	13780	85176	7150	30632	2407	42175	3407	89159	7499
September	10960	97261	8208	135457	11564	141901	12132	90360	7604
October	9520	139239	11878	115122	9758	81387	6809	66866	5545
November	8840	82642	6916	43314	3499	29869	2337	7225	384
December	9520	57738	4744	43607	3521	33730	2668	26750	2065

*The priority structure is,

1) M&I water supply (M&I)
2) Downstream water supply (D)
3) Recreation (R)
4) Hydroelectric power generation (P)
5) Flood control (FC).

Probability levels for recreation and flood control are 0.90.

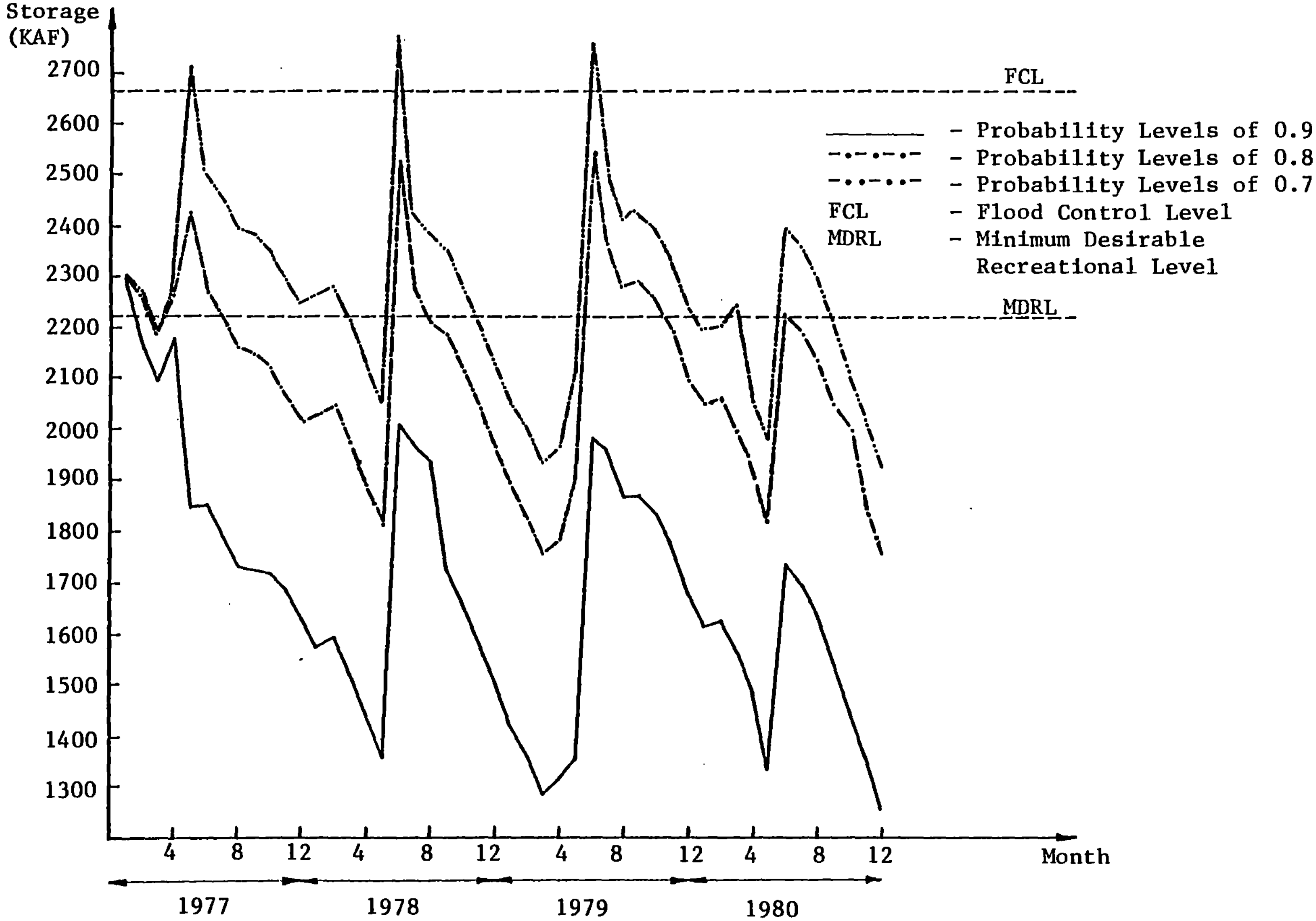

Figure 10. Projected Storage of Denison Reservoir With Priority Structure: FC, M&I, D, P, R

to be conflicting with flood control. Also, during low inflow periods it tends to be conflicting with the goals of M&I water supply, downstream water supply, and hydroelectric power generation. Flood control tends to force a large amount of release during high inflow periods and can cause water shortage in later periods when inflows are low. The reservoir manager can modify the target values of these goals in order to obtain his preferred solution. For example, he may reduce the power targets during recreational months if the storage level seems to be too low. However, during winter months when recreational visits to the reservoir are low the power targets can be increased in order to generate more revenue. Figure 11 shows the projected storages of Denison reservoir when the monthly power demands are increased by 10% and 20%. As expected, the reservoir storage will be lowered down quickly with higher power targets during low inflow periods.

Probability Level

Flood control and recreation are probabilistic goals and their respective probability levels, β and η, need to be specified. For flood control purpose, the higher the probability level, the more release is required. On the other hand, less release is desired for recreational goal with higher probability level. Thus, these two goals tend to become highly conflicting with high probability levels. The effect on the model due to variations in these parameters depends highly on the priority structure. If flood control is the dominating goal, the model will be very sensitive to the probability level. In order to be highly confident that the flood control level is not exceeded, the storage will be kept very low. An example of this case is

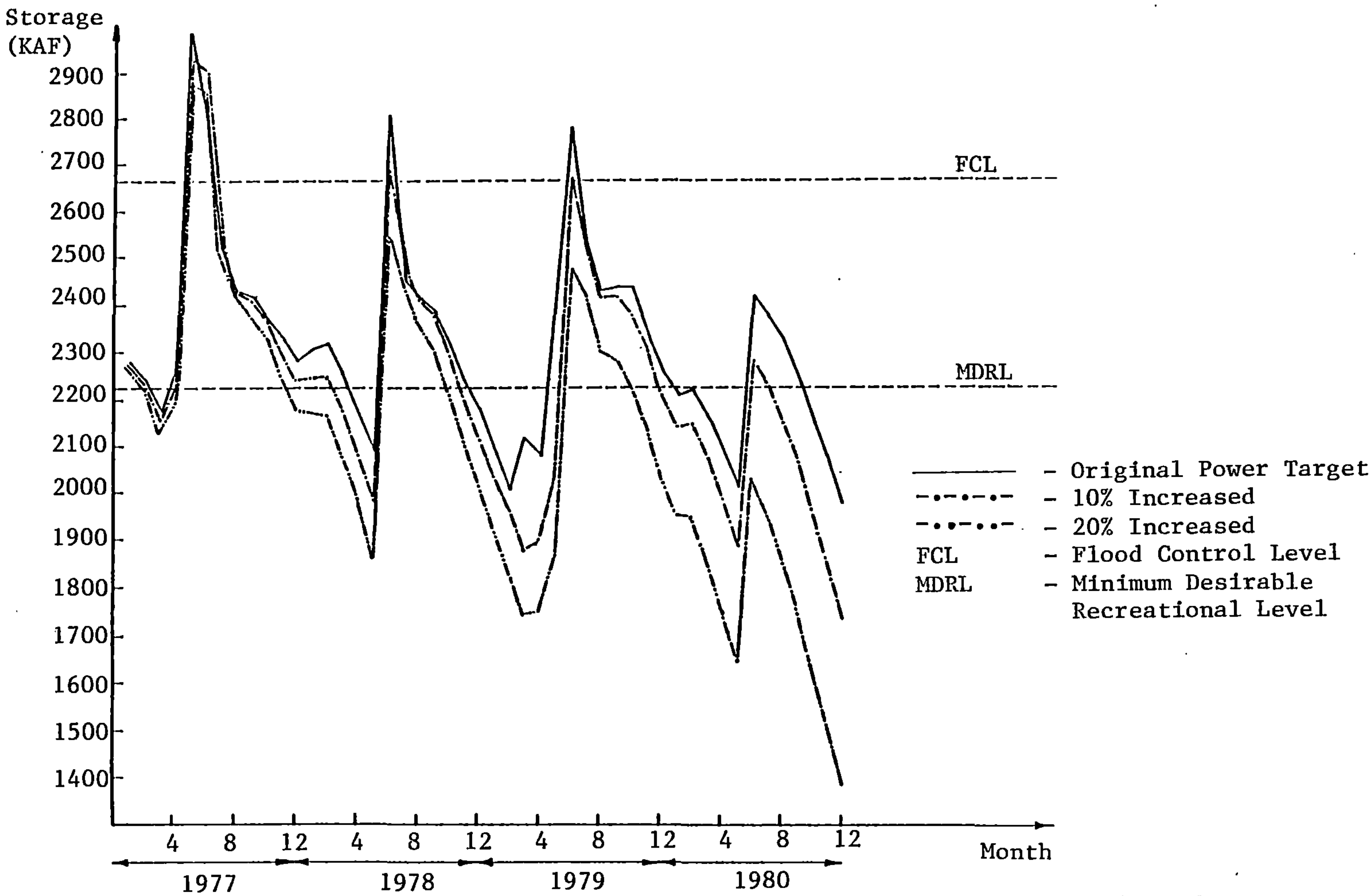

Figure 11. Projected Storage of Denison Reservoir With 10% and 20% Increased in Power Targets (Priority Structure is: M&I, D, P, R, FC)

shown is Figure 10. However, with recreation ranked higher than flood control, the model seems to be much less sensitive with respect to the probability levels. Figures 9 and 12, using Denison reservoir as the example, illustrate this case.

Summary

This chapter illustrates the use of the CCGP model developed in Chapter IV by applying it to a real reservoir system. The system is a portion of the Red River system and consists of three reservoirs: Denison, Broken Bow, and Pine Creek. The chapter starts with the system description. Pertinent data required are then identified and provided in Appendix C. The computations of conditional CDF's are also illustrated. Comparisons of nonconditional and conditional CDF's show that the use of nonconditional CDF's, as in many studies, tends to give less accurate results. The release decision for the years 1977-1980 is identified using the proposed methodology. Sensitivity analysis of the model based on three important parameters: priority structure, target values, and probability levels is also discussed and performed using Denison reservoir as the example. Due to conflicting natures of the goals, there is no general operating rule which completely satisfies all of them. Thus, preference information from the reservoir manager is usually required with frequent updating in order to obtain a compromise solution. The use of the interactive program in modifying decisions from one iteration to the next is very appropriate.

In general, the requirements from M&I and downstream water supplies are relatively small but need to be satisfied. Thus, they should be ranked among the top goals. Excess amount of water should always be

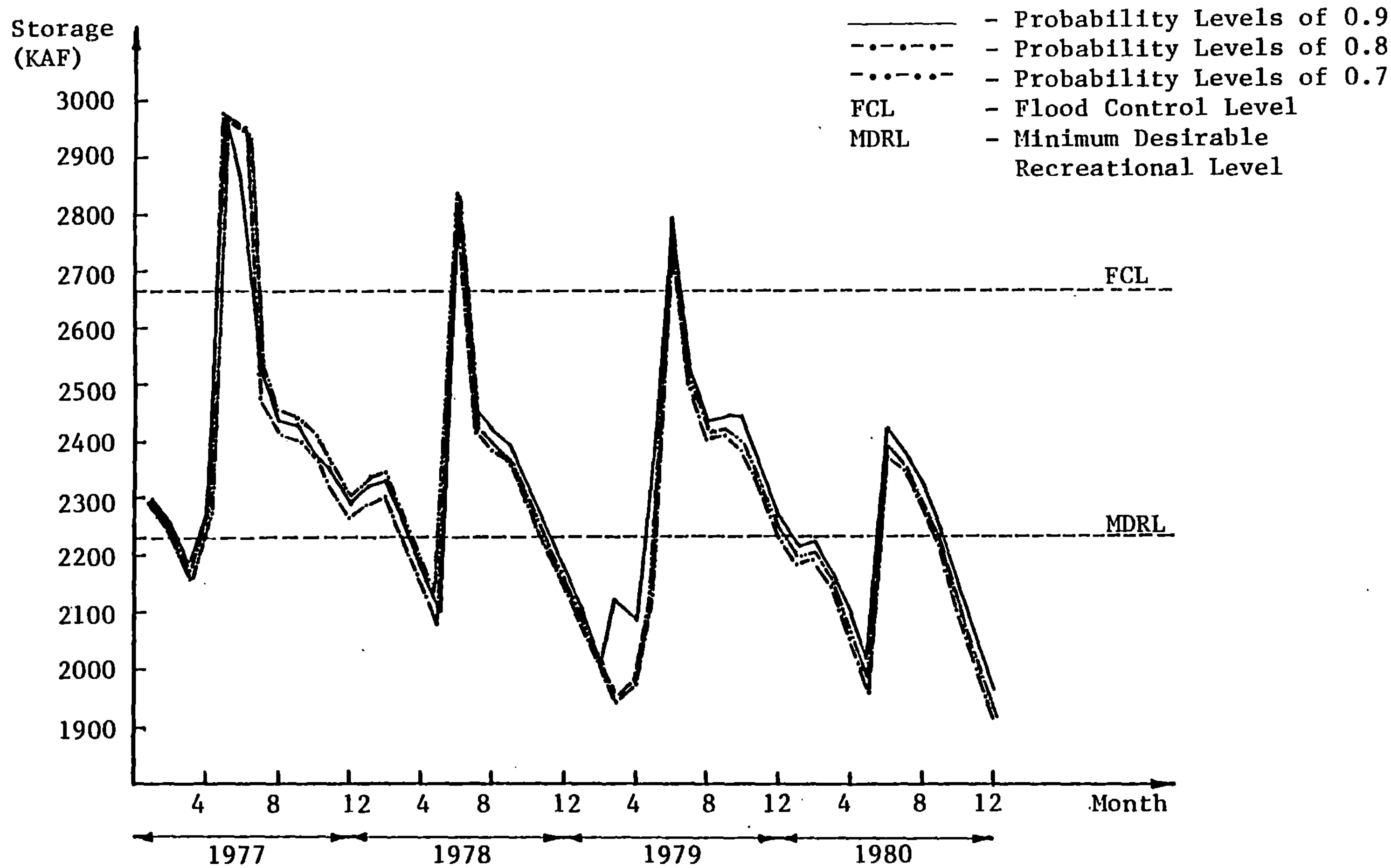

Figure 12. Projected Storage of Denison Reservoir With Priority Structure: M&I, D, P, R, FC

released through the turbine in order to generate more power. The probability goals of recreation and flood control tend to guard against extreme events. That is, release is generally limited by recreational goal to compensate for the chance of low runoff during the next period. However, flood control tends to force a large amount of release so that flooding will not occur if an extremely large inflow is faced in the next period. The model is very sensitive to the difference in probability levels if flood control is the dominating goal.

For the three-reservoir system analyzed in this chapter, the results from the actual operation seems to be comparable with the case in which the priority structure is: M&I, D, P, R, FC. However, observations from figures 6-8 reveal that the goals of M&I water supply, downstream water supply, and hydroelectric power generation may not be completely satisfied at all times with the actual operation. In this respect, the results given by the model tend to be superior. For Denison and Broken Bow reservoirs, the storages are usually low during the early and late parts of the year in order to satisfy the power demands. During the middle of the year when recreational visits to the reservoirs are normally high, the storages are usually well above the minimum desirable recreational levels. Although the power targets for these reservoirs are reasonably high, increase of up to 20% seems to be possible. The amount of power generated will be drastically reduced if the recreational level is desired to be maintained throughout the year. For Pine Creek reservoir, the magnitude of the inflow is relatively large comparing to the size of the reservoir. Thus, there is always possibility that the flood control level is exceeded even with the storage at the beginning of the period being kept as low as allowed. High degrees of fluctuations in the storage level seems to be unavoidable.

CHAPTER VI

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This chapter summarizes all the steps carried out in order to accomplish the objectives of this research. Conclusions from this study are then provided. Finally, recommendations of future works and possible extensions of this research are outlined.

Summary

Chapter I of this research provides the problem statement. Introduction of the reservoir operation problems and descriptions of its characteristics are given. The research objectives which involve primary and secondary objectives are then identified. Extensive literature survey of the reservoir operation problem is given in Chapter II. The research efforts in this area are categorized into three major classes: systems with single objective and deterministic inflows, systems with single objective and stochastic inflows, and systems with multiple objectives and deterministic inflows. This research problem may be considered as the fourth class, that is, systems with multiple objectives and stochastic inflows. Chapter III introduces the concepts of multiple-objective decision making (MODM). Descriptions of goal programming which is the methodology adopted in the solution procedures, and its extensions are given. Chapter IV involves the model development of the research problem and the solution procedures. An application of this model to a real multiple-reservoir system is shown in Chapter V. Description of the computer program based on the solution procedures and the program listing are provided in Appendixes A and B, respectively. Finally, the data used in Chapter V are listed in Appendix C.

In order to fulfill the primary and secondary objectives, the following accomplishments have been achieved:

1) Development of a mathematical model for the reservoir operation problem which involves multiple objectives, stochastic inflows, and multiple reservoirs. The model is designed to be applicable to any type of system configuration with minimum modifications.

2) Development of conditional cumulative distribution functions based on normal and lognormal distributions in order to handle the correlation between inflows in successive periods.

3) Development of the solution procedures to solve for the release decision. The concept of goal programming is adopted in order to find the compromise solution. The procedure is designed to be interactive so that decisions can be modified iteratively until a satisfactory solution is reached.

4) Development of the computer program based on the solution procedures.

5) Application of the proposed methodology to a three-reservoir system which is a portion of the Red River reservoir system. The results obtained are analyzed and compared to the actual operation.

6) Sensitivity analysis of the model based on three important parameters: priority structure, target value, and probability level has been performed. Discussions are made with respect to the general

system and the three-reservoir system analyzed in this research.

Conclusions

The reservoir operation problem is one of the most active areas of research in water resources systems. The use of system analysis in solving for operating policies has been very popular during the past two decades and has proved to be very beneficial. As evidenced in the literature review, almost every optimization methodology has been applied to the problem. The effectiveness of each methodology depends highly on the viewpoint about the system characteristics. At present, considerable attention has been directed to solving large-scale systems with stochastic inflows. The multiple-objective aspect of the problem is also the recent interest among researchers in this area.

This research introduces a model which can handle large-scale multipurpose reservoir systems with stochastic inflows. There have been very few models which include all of these characteristics. In addition to satisfying the objectives set forth in Chapter I, the methodology developed in this research has the following desirable features:

1) The model is designed to be flexible so that any type of system configuration can be considered. It can be used for planning and/or real-time purposes.

2) Extensive economic analysis is not required. The data needed in the model are usually available in most systems. The use of "target-based" objective function greatly reduces the need to collect "economic-based" data which are difficult to obtain.

3) The solution obtained is realistic and meaningful. The

interactive programming allows the user to perform trade-offs among conflicting objectives so that a nondominated and satisfactory solution can be obtained. The use of conditional CDF's which consider the correlation between inflows can improve the accuracy of the results.

4) Effort and time required from the user in interacting with the program are not excessive. As an example, the monthly release decision for the three-reservoir system analyzed in Chapter V (with a planning horizon of 12 months) can usually be obtained in less than 10 minutes. For each month, the user may need to adjust his decision two to three times before a satisfactory solution is reached. The CPU time required by VAX 11/780 computer for each iteration is approximately 35 seconds.

Recommendations

Although there has been a large amount of work done, research in this area is still very active. The literature survey in Chapter II provides some ideas about the further work. Recommendations will be given with respect to the general case and with respect to possible extensions of the methodology developed in this study.

The General Problem

Possible further works with respect to the general reservoir operations problem are as follows:

1) For systems with single objective and deterministic inflows, there are a number of methodologies which can handle large-scale systems efficiently in terms of computational requirements. As mentioned in Chapter II, promising methodologies are constrained differential

dynamic programming, binary state dynamic programming, the principle of progressive optimality, and network flow algorithm. In testing many of these methodologies, hypothetical systems are considered. Applications to real systems are still relatively few. Also, direct comparisons among these methodologies are difficult since each methodology uses different system for testing. Thus, it would be interesting to test each of them with a common real world system. Comparisons can then be made with respect to quality of the solution obtained and computational requirements.

2) In stochastic dynamic programming, discretization of storage and inflow is necessary. However, this is usually done in a trial and error manner. A theoretically correct scheme which identifies the minimum number of storage levels and inflows would be a useful contribution.

3) At present, much attention has been directed to improving stochastic dynamic programming algorithms in order to handle large-scale systems. However, there is still no algorithm which can be effectively applied to systems of more than two reservoirs. Research in this direction is very challenging and, if successful, will be a significant breakthrough.

4) Development of a multiple-objective stochastic dynamic programming algorithm is another possible extension. This can then be applied to small systems of multipurpose reservoirs.

5) In the multiple-objective dynamic programming algorithm introduced by Tauxe et al. (1979a,b), the conventional dynamic programming was used in solving each subproblem. Improvement in this direction can be made by replacing the conventional dynamic programming by

its variants described in Chapter II. Applications of such an algorithm to real systems would be desirable.

The Research Problem

Possible extensions of this research are as follows:

1) In this research, all the reservoirs in the system are considered to be completely built and there is no need for future expansion. In reality, new systems may be proposed or existing reservoirs may need to be enlarged. Thus, incorporating capacity expansion into the model is a possible topic.

2) Due to the nonlinearity of the hydroelectric power function, a nonlinear goal programming algorithm may be used as an alternative to the linearization scheme employed in this research. However, much longer computational time should be expected. Development of an efficient nonlinear goal programming to solve the problem is another possible topic.

3) Only one period correlation of inflows has been assumed in this research. Correlations of two or more periods may be considered.

4) The conditional cumulative distribution functions have been developed based on normal and lognormal distributions. Other types of distributions such as gamma, Weibull, inverse Gaussian, or others may be considered.

5) Various demands in the model are assumed to be known with certainty. This assumption can be relaxed. Also, variations in demands due to variations in the cost of water may be considered. This will lead to the price sensitive problem.

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APPENDIXES

APPENDIX A

DESCRIPTION OF THE COMPUTER PROGRAM

Introduction

This appendix provides the description of the computer program of the chance-constrained goal programming developed in this research. First, definitions of various parameters used in the program are given. Second, the organization of files in the program is outlined. Third, the structure of the program and relationships among subroutines are provided. Finally, the guideline for the interactive decision making procedure is also given.

Definition of Parameters

The following parameters are used in the computer program:

NDATA	=	number of historical inflow data.
ICODE	=	type of distribution function of inflow, 1 - normal distribution 2 - lognormal distribution.
CAREA1, CAREA2	=	coefficients resulting from the regression analysis of surface area against reservoir storage.
IELINE	=	number of segments used to linearize the curve of energy rate against reservoir storage.
ICLINE	=	number of segments used to linearize the curve of power plant capacity against reservoir storage.
CERATEA, CERATEB	=	coefficients resulting from the regression analysis of energy rate against reservoir storage for each segment. Enter '0' for both parameters for nonpower reservoirs.
SERATE	=	upper limit of the reservoir level for each IELINE.
CCAPA,CCAPB	=	coefficients resulting from the regression analysis of power plant capacity against reservoir storage. Enter '0' for both parameters for nonpower reservoirs.
SCAP	=	upper limit of the reservoir level for each ICLINE.

MONTH	=	name of the month in full.
AVEV	=	evaporation from the reservoir during the month, in inches.
SINIT	=	last period reservoir storage, in acres-feet.
HOUR	=	number of hours that the power plant is operated during the month.
X	=	historical inflows of the month.
NROW	=	number of rows.
ANAME	=	the name of each purpose, CONS - constraint FLCN - flood control MIWS - M&I water supply DFWS - downstream water supply GELC - hydroelectric power generation RECL - recreation
JCOUNT	=	number of rows used in forming the objective function.
SIGN(JCOUNT)	=	type of deviational variable to be minimized, POS - positive deviation NEG - negative deviation
RPW(1,JCOUNT)	=	row location of the negative or positive deviational variable.
RPW(2,JCOUNT)	=	priority level of the goal corresponding to the negative or positive deviational variable. All constraints must be assigned with the highest priority, i.e. 1.
RPW(3,JCOUNT)	=	weight assigned to the above priority level.
ICOUNT	=	number of rows used to provide information about the technological coefficients of all decision variables.
CRV(1,ICOUNT)	=	column location of each decision variable.
CRV(2,ICOUNT)	=	row location of each decision variable. All rows associated with the first decision variable must be entered before the next decision can be entered.
CRV(3,ICOUNT)	=	coefficient of the decision variable.

PRIORITY = information about the priority structure. The name of the highest priority goal should be entered first.
FC - flood control
D - downstream water supply
M&I- municipal and industrial water supply
P - hydroelectric power generation
R - recreation.

RGHT = information about the target value.
RGHT - all nonpower goals and constraints
GELC - hydroelectric power goal
CELC - constraint on power plant capacity.

PROB = probability levels for probabilistic goals and constraints. Enter '0' for deterministic goals and constraints.

ORHS = right hand side value of the goal or constraint.

NORES = reservoir number. For example, the reservoirs in Chapter V are numbered as follows:
1 - Denison
2 - Broken Bow
3 - Pine Creek.

File Organization

The computer program involves both input and output files. The number of input files required is equal to the number of reservoirs in the system plus one other file for the goal programming routine. Two output files which provide the results about conditional CDF's and release decisions are generated by the program.

Input File

Two types of input files are required. The first type corresponds to the characteristics of each reservoir. The second type is for the goal programming routine. The data required and their formats in these files are as follows:

Reservoir Characteristic File

One file is needed for each reservoir in the system. The formats of the data to be entered in this file are shown in brackets.

1) Record 1. (I3,I2).
   NDATA,ICODE.

2) Record 2. (F10.2,F10.7)
   CAREA1, CAREA2.

3) Record 3. (2I2).
   IELINE,ICLINE.

4) Records 4- 4+IELINE. (F10.2,F10.7,F10.2).
   CERATEA, CERATEB, SERATE.
   For nonpower reservoirs, enter '0' for all fields.

5) Records (5+IELINE) - (5+IELINE + ICLINE).
   (F10.2, F10.7, F10.2).
   CCAPA, CCAPB, SCAP
   For nonpower reservoirs, enter '0' for all fields.

6) Record (6 +IELINE +ICLINE). (A10,F5.2,F10.2, F6.2).
   MONTH, AVEV, SINIT, HOUR.

7) Records (7 + IELINE + ICLINE) - (7+IELINE + ICLINE + NDATA). (F10.3)
   X.

8) Repeat (1)-(7) for each of the next month, i.e. February, March, ..., December.

Goal Programming File

Only one input file of this type is required by the program. The data to be entered into this file are related to the priority structure of various goals, target values, and constraints of the problem. The problem must be in the form of the chance-constrained goal programming formulation developed in Chapter IV, that is, in the form of (4.26)-(4.40). The data in the quotation mark are to be entered as shown.

1) Record 1. (A4).
'MNTH'.

2) Record 2. (A4,A10).
'MNTH',MONTH.

3) Record 3. (A4,I3).
'ROWS',NROW.

4) Record 4. (A4,(NROW)(A1)).
'ROWS',(NROW)('B').

5) Record 5-(5+JCOUNT). (A4,A3,3F10.2).
ANAME,SIGN(JCOUNT),RPW(1,COUNT),RPW(2,JCOUNT),
RPW(3,JCOUNT).

6) Record (6+JCOUNT). (A4,A3,3F10.2).
'OBJT','END','0.00','0.00','0.00'.

7) Records (7+JCOUNT)-(7+JCOUNT+ICOUNT). (A4,3F10.2).
'DAT1',CRV(1,ICOUNT),CRV(2,ICOUNT),CRV(3,ICOUNT).
The first decision variable must be entered first, then the second decision variable can be entered, and so on.

8) Record (8+JCOUNT+ICOUNT). (A4,3F10.2).
'DAT1','0.00','0.00','0.00'.

9) Record (9+JCOUNT+ICOUNT). (A4,A10).
'PRIO','CONSTRAINT'.

10) Records (10+JCOUNT+ICOUNT)-(10+JCOUNT+ICOUNT+NPRT).
(A4,A10).
'PRIO',PRIORITY.

11) Records (11+JCOUNT+ICOUNT+NPRT) - (11+JCOUNT+ICOUNT+NPRT+NROW). (A4,F5.2,F15.2,I2).
RGHT,PROB,ORHS,NORES.

12) Repeat (1)-(11) for each of the next month, i.e.
February, March, ..., December.

Output File

The results from the computer program are written in two output files. The first file provides the historical inflow data of previous and current months, the correlation coefficient of inflows between the two months, and the conditional CDF of the current month inflow based on the previous month inflow. These values are given for each reservoir in the system. The second file provides the release decisions determined from the chance-constrained goal programming routine. As an example, the outputs for Denison reservoir during the month of February are shown below:

Conditional CDF File

FOR THE MONTH OF JANUARY (RESERVOIR 1)

OBSERVED DATA:

610.00	2830.00	742.00	1581.00	4489.00
2046.00	1487.00	1532.00	1326.00	13418.00
2714.00	1723.00	685.00	1028.00	2394.00
2474.00	1461.00	90.00	2142.00	2734.00
2769.00	1061.00	1757.00	7797.00	1562.00
999.00	1341.00	2940.00	1115.00	528.00
260.00	989.00	751.00	571.00	452.00
4615.00	501.00	6484.00	2124.00	1230.00
1044.00	408.00	1446.00	1116.00	492.00

OBSERVED DATA IN ASCENDING ORDER:

90.00	260.00	408.00	452.00	492.00
501.00	528.00	571.00	610.00	685.00
742.00	751.00	989.00	999.00	1028.00
1044.00	1061.00	1115.00	1116.00	1230.00
1326.00	1341.00	1446.00	1461.00	1487.00
1532.00	1562.00	1581.00	1723.00	1757.00
2046.00	2124.00	2142.00	2394.00	2474.00
2714.00	2734.00	2769.00	2830.00	2940.00
4489.00	4615.00	6484.00	7797.00	13418.00

LOG-TRANSFORMED DATA IN ASCENDING ORDER:

4.50	5.56	6.01	6.11	6.20
6.22	6.27	6.35	6.41	6.53
6.61	6.62	6.90	6.91	6.94
6.95	6.97	7.02	7.02	7.11
7.19	7.20	7.28	7.29	7.30
7.33	7.35	7.37	7.45	7.47
7.62	7.66	7.67	7.78	7.81
7.91	7.91	7.93	7.95	7.99
8.41	8.44	8.78	8.96	9.50

MEAN = 7.21667 VARIANCE = 0.82900

FOR THE MONTH OF FEBRUARY (RESERVOIR 1)

OBSERVED DATA;

3911.00	1719.00	745.00	1019.00	4735.00
2769.00	1098.00	5028.00	5484.00	12031.00
1058.00	1672.00	493.00	810.00	1304.00
19628.00	706.00	411.00	7029.00	2691.00
1629.00	4139.00	7676.00	9595.00	871.00
4651.00	7134.00	4435.00	2436.00	811.00
292.00	254.00	1136.00	1541.00	1279.00
2227.00	554.00	7159.00	2914.00	1755.00
1572.00	1345.00	2443.00	3928.00	501.00

OBSERVED DATA IN ASCENDING ORDER:

254.00	292.00	411.00	493.00	501.00
554.00	706.00	745.00	810.00	811.00
871.00	1019.00	1058.00	1098.00	1136.00
1279.00	1304.00	1345.00	1541.00	1572.00
1629.00	1672.00	1719.00	1755.00	2227.00
2436.00	2443.00	2691.00	2769.00	2914.00
3911.00	3928.00	4139.00	4435.00	4651.00
4735.00	5028.00	5484.00	7029.00	7134.00
7159.00	7676.00	9595.00	12031.00	19628.00

LOG-TRANSFORMED DATA IN ASCENDING ORDER:

5.54	5.68	6.02	6.20	6.22
6.32	6.56	6.61	6.70	6.70
6.77	6.93	6.96	7.00	7.04
7.15	7.17	7.20	7.34	7.36
7.40	7.42	7.45	7.47	7.71
7.80	7.80	7.90	7.93	7.98
8.27	8.28	8.33	8.40	8.44
8.46	8.52	8.61	8.86	8.87
8.88	8.95	9.17	9.40	9.88

MEAN = 7.59164 VARIANCE = 1.04617

FOR RESERVOIR 1 THE COEFFICIENT OF CORRELATION
BETWEEN THE MONTHS OF JANUARY AND FEBRUARY
IS 0.6371

CONDITIONAL MEAN = 7.86663
CONDITIONAL STD. DEV. = 0.78838

NUMBER	CURRENT INFLOW	NONCONDITIONAL CDF	CONDITIONAL CDF
1	254.00	0.022	0.002
2	292.00	0.031	0.003
3	411.00	0.062	0.010
4	493.00	0.087	0.017
5	501.00	0.089	0.018
6	554.00	0.106	0.025
7	706.00	0.156	0.049
8	745.00	0.169	0.056
9	810.00	0.191	0.069
10	811.00	0.191	0.069
11	871.00	0.211	0.082
12	1019.00	0.258	0.117
13	1058.00	0.270	0.126
14	1098.00	0.282	0.136
15	1136.00	0.293	0.146
16	1279.00	0.334	0.183
17	1304.00	0.341	0.190
18	1345.00	0.352	0.200
19	1541.00	0.403	0.252
20	1572.00	0.410	0.260
21	1629.00	0.424	0.275
22	1672.00	0.434	0.286
23	1719.00	0.445	0.298
24	1755.00	0.453	0.308
25	2227.00	0.545	0.420
26	2436.00	0.580	0.465
27	2443.00	0.581	0.467
28	2691.00	0.618	0.516
29	2769.00	0.628	0.530
30	2914.00	0.647	0.556
31	3911.00	0.747	0.696
32	3928.00	0.748	0.698
33	4139.00	0.764	0.721
34	4435.00	0.785	0.750
35	4651.00	0.798	0.768
36	4735.00	0.803	0.775
37	5028.00	0.819	0.797
38	5484.00	0.840	0.827
39	7029.00	0.892	0.896
40	7134.00	0.895	0.899
41	7159.00	0.895	0.900
42	7676.00	0.907	0.914
43	9595.00	0.938	0.951
44	12031.00	0.961	0.974
45	19628.00	0.988	0.995

Release Decision File

FOR THE MONTH OF FEBRUARY ,THE RESULTS ARE AS FOLLOWS:

FOR RESERVOIR NUMBER 1:
THE PREVIOUS PERIOD INFLOW(AC-FT) IS 119010.00
THE PREVIOUS PERIOD RESERVOIR STORAGE (AC-FT) IS 2398800.00

FOR RESERVOIR NUMBER 2:
THE PREVIOUS PERIOD INFLOW(AC-FT) IS 47604.00
THE PREVIOUS PERIOD RESERVOIR STORAGE (AC-FT) IS 714040.00

FOR RESERVOIR NUMBER 3:
THE PREVIOUS PERIOD INFLOW(AC-FT) IS 47604.00
THE PREVIOUS PERIOD RESERVOIR STORAGE (AC-FT) IS 46650.00

(1). ANALYSIS OF DEVIATIONS FROM TARGET AMOUNTS

PURPOSE		TARGET AMOUNT	ACTUAL AMOUNT	POSITIVE DEVIATION	NEGATIVE DEVIATION
RELEASE FOR M&I WATER SUPPLY(AC-FT):					
RESERVOIR NO. 1	=>	2762.00	2762.00	0.00	0.00
RESERVOIR NO. 2	=>	5985.00	5985.00	0.00	0.00
RESERVOIR NO. 3	=>	7734.00	7734.00	0.00	0.00
RELEASE FOR DOWNSTREAM FLOW(AC-FT):					
RESERVOIR NO. 1	=>	0.00	112002.79	112002.79	0.00
RESERVOIR NO. 2	=>	10128.00	30027.41	19899.41	0.00
RESERVOIR NO. 3	=>	3314.00	12020.57	8706.57	0.00
HYDROPOWER GENERATION(MWH):					
RESERVOIR NO. 1	=>	9624.00	9624.00	0.00	0.00
RESERVOIR NO. 2	=>	4480.00	4480.00	0.00	0.00
RESERVOIR NO. 3	=>	0.00	0.00	0.00	0.00
RELEASE FOR FLOOD CONTROL(AC-FT):					
RESERVOIR NO. 1	=>	152383.09	114764.79	0.00	37618.30
RESERVOIR NO. 2	=>	133876.01	36012.41	0.00	97863.60
RESERVOIR NO. 3	=>	188756.37	19754.57	0.00	169001.80
RELEASE FOR RECREATION(AC-FT):					
RESERVOIR NO. 1	<=	49143.54	114764.79	65621.26	0.00
RESERVOIR NO. 2	<=	0.00	36012.41	36012.41	0.00
RESERVOIR NO. 3	<=	19754.57	19754.57	0.00	0.00

(2). RELEASES FROM RESERVOIRS(AC-FT)

	RESERVOIR 1	RESERVOIR 2	RESERVOIR 3
NORMAL RELEASE(FOR POWER OR NON POWER GENERATION)	112002.79	30027.41	12020.57
RELEASE FOR M&I WATER SUPPLY	2762.00	5985.00	7734.00
RELEASE THROUGH SPILLWAY	0.00	0.00	0.00

(3). ANALYSIS OF PRIORITY STRUCTURE

PRIORITY 1 - CONSTRAINT	0.00
PRIORITY 2 - M&I	0.00
PRIORITY 3 - D	0.00
PRIORITY 4 - P	0.00
PRIORITY 5 - R	101633.67
PRIORITY 6 - FC	304483.69

FC - FLOOD CONTROL
R - RECREATION
P - POWER GENERATION
M&I - MUNICIPAL AND INDUSTRIAL WATER SUPPLY
D - DOWNSTREAM WATER SUPPLY

Program Structure

The program consists of 10 routine which are MAIN, CALC, ERF, MDNRIS, MERFI, COLUMN, ROW, UPDATE, OUTPUT, and CHANGE. The functions of each routine are provided in the program listing in Appendix B. The structure of the program is shown in Figure 13.

Interactive Decision Making Procedure

As mentioned earlier, the computer program is designed to be interactive so that the decision maker can participate during the analysis. At each iteration, the result for each time period is displayed on the terminal. If it is not satisfactory then he can modify his decision with respect to: priority structure, target value, and probability level. This process continues until the result for that time period is satisfactory.

If a new priority structure is desired, the program will display the previous priority level and weight of each objective. The user can enter the new priority level and weight for each objective that needs to be modified. The new number of priority levels and the name of each objective are then requested.

If modification is made with respect to the target value, the program will display the previous target according to each objective. The new target can then be entered for each purpose.

Finally, the goals of flood control and recreation are probabilistic. Thus, modification with respect to the probability level can be made for them. The probability level for each of the two goals during the previous iteration is first prompted, the new value can then be entered if desired.

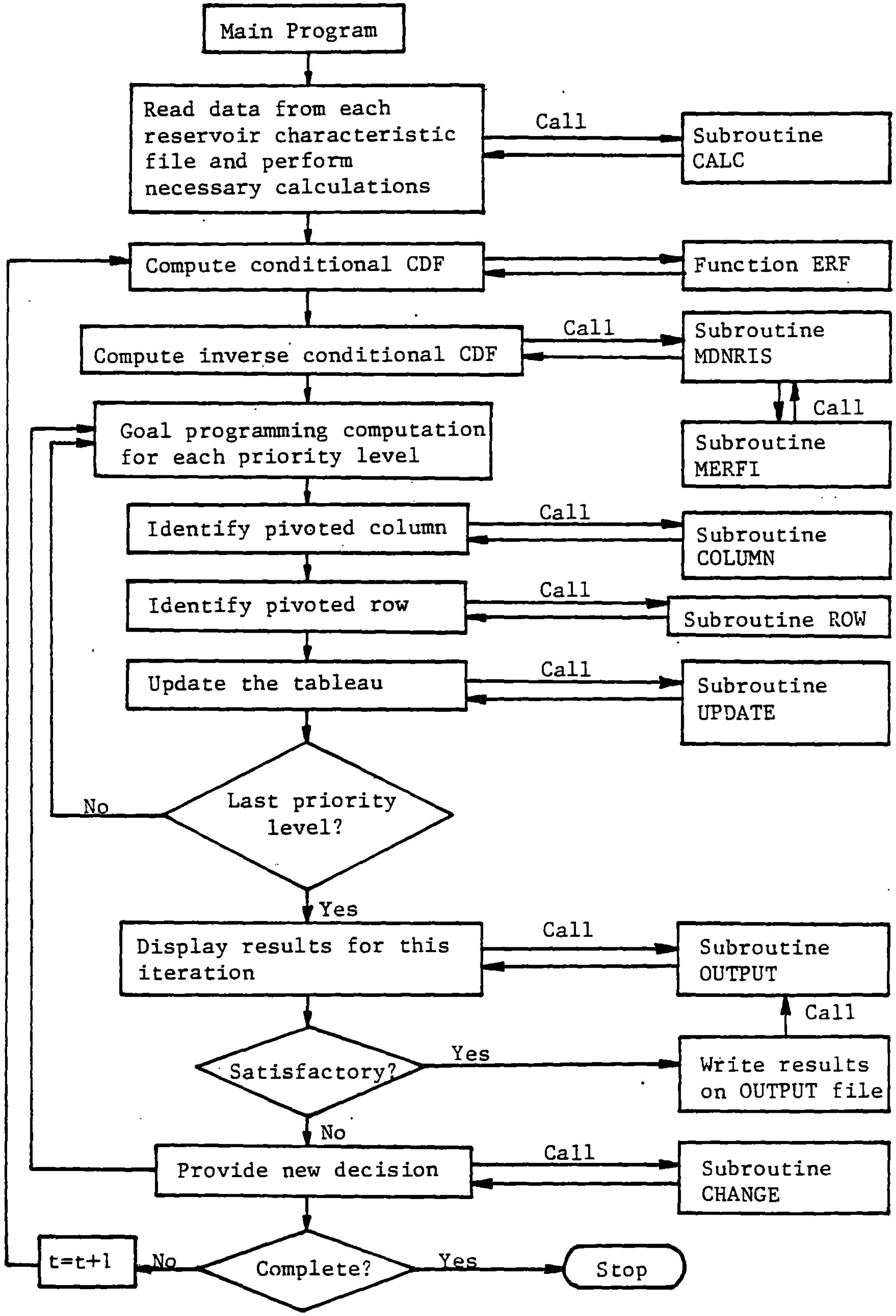

Figure 13. Program Structure

When all modifications have been made, the user can exit the modification routine. The program will automatically adjust the new problem to the standard form of the chance-constrained goal programming algorithm. Computations for this iteration can then be carried out.

APPENDIX B

FORTRAN PROGRAM LISTING

```
C************************************************************C
C                                                            C
C        THIS INTERACTIVE PROGRAM IS DESIGNED TO SOLVE       C
C   THE RESERVOIR OPERATION PROBLEM WITH STOCHASTIC          C
C   INFLOW. THE PROBLEM INVOLVES SEVERAL CONFLICTING         C
C   OBJECTIVES WHICH ARE FLOOD CONTROL, M&I WATER SUPPLY,    C
C   DOWNSTREAM WATER SUPPLY, RECREATION, HYDROELECTRIC       C
C   POWER GENERATION, AND DROUGHT PROTECTION. THE DECISION   C
C   IDENTIFIED BY THIS PROGRAM IS THE SCHEDULED RELEASE      C
C   FOR EACH PERIOD. THE CONCEPT OF GOAL PROGRAMMING IS      C
C   EMPLOYED IN SOLVING FOR THE COMPROMISE SOLUTION.         C
C                                                            C
C        THERE ARE 10 ROUTINES IN THIS PROGRAM: MAIN,        C
C   CALC, ERF, MDNRIS, MERFI, COLUMN, ROW, UPDATE, OUTPUT,   C
C   AND CHANGE. THE RESPECTIVE FUNCTIONS ARE PROVIDED AT     C
C   THE BEGINNING OF EACH ROUTINE.                           C
C                                                            C
C************************************************************C
C                                                            C
C          WRITTEN BY CHAWENGSAK CHANGCHIT                   C
C     SCHOOL OF INDUSTRIAL ENGINEERING AND MANAGEMENT        C
C       DISSERTATION ADVISOR: DR. M. PALMER TERRELL          C
C                                                            C
C************************************************************C
C                                                            C
C                     MAIN ROUTINE                           C
C                     ============                           C
C                                                            C
C        THE MAIN ROUTINE OBTAINS THE HISTORICAL             C
C   INFLOW DATA, MEAN AND STANDARD DEVIATION OF MONTHLY      C
C   INFLOW BY CALLING SUBROUTINE CALC. IT THEN CALCULATES    C
C   THE CORRELATION COEFFICIENT BETWEEN TWO SUCCESSIVE       C
C   MONTHS, CONDITIONAL MEAN, AND CONDITIONAL STANDARD       C
C   DEVIATION. NEXT, THE CONDITIONAL CDF OF THE MONTH        C
C   INFLOW IS COMPUTED BY FUNCTION ERF. THE PROGRAM THEN     C
C   READS DATA FROM THE GOAL PROGRAMMING FILE. FOR PROB-     C
C   BABILISTIC GOALS AND PROBABILISTIC CONSTRAINTS, THE      C
C   ASSOCIATED INVERSE CDF'S ARE COMPUTED BY CALLING         C
C   SUBROUTINE MDNRIS. THE PROBLEM IS CONVERTED TO THE       C
C   STANDARD FORM AND SOLVED ACCORDING TO THE REVISED        C
C   SIMPLEX-BASED GOAL PROGRAMMING ALGORITHM. THIS           C
C   INVOLVES SUBROUTINES COLUMN, ROW, AND UPDATE WHICH       C
C   RESPECTIVELY IDENTIFIES THE PIVOTED COLUMN, IDENTIFIES   C
C   THE PIVOTED ROW, AND UPDATES THE NEW TABLEAU. WHEN       C
C   THE SOLUTION FROM THIS ITERATION IS OBTAINED,            C
C   SUBROUTINE OUTPUT IS CALLED TO DISPLAY THE RESULT.       C
C   IF THE RESULT IS SATISFACTORY, IT IS WRITTEN INTO THE    C
C   RELEASE DECISION FILE. OTHERWISE, THE PROBLEM CAN BE     C
C   MODIFIED THROUGH THREE PARAMETERS: PRIORITY STRUCTURE,   C
C   TARGET VALUES, AND PROBABILITY LEVELS. SUBROUTINE        C
C   CHANGE IS CALLED TO PERFORM THIS FUNCTION. THE GOAL      C
C   PROGRAMMING ANALYSIS IS THEN CARRIED OUT AGAIN. THIS     C
```

```
C   PROCESS CONTINUES UNTIL THE SOLUTION OBTAIN IS           C
C   SATISFACTORY.                                            C
C                                                            C
C************************************************************C
C
C
C
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION DIFF1(10,100),DIFF2(10,100),X1(100),X2(100)
      DIMENSION ZCELS2(100),ZCELS21(100),DIFF(100)
      DIMENSION PREV1(10),SUMXX1(10),SUMXX2(10)
      DIMENSION STD1(10),STD2(10),XBAR1(10),XBAR2(10)
      DIMENSION PAVEV(10),CAVEV(10)
      DIMENSION PRIORITY(15)
      COMMON /B10/ NVAR,NPRT,NUMDEV,RVLX(15,350),KPOS(150),MBAS(350)
      COMMON /B20/ C(150,350),ZVAL(15),CONST
      COMMON /B30/ NCOL,A(3500),KCOL(350),Y(150),VALX(2,350),LPRT
      COMMON /B40/ T(4),RHS1(150),X(150),NROW,VALY(150,2)
      COMMON /B50/ EE(10000),IP(500),NONZERO(250)
      COMMON /B60/ IE(10000),IRC(3500),KL(350),MTRANS
      COMMON /B70/ SIGN(150),EQUALS(150)
      COMMON /B80/ CRV(3,2451),RPW(3,141),RHS(150),ORHS(150)
      COMMON /B90/ NDATA,ICODE,II,SINIT(10),HOUR(10),SLAST(10)
      COMMON /B100/ CAREA1(10),CAREA2(10),CERATE1(10),CERATE2(10)
      COMMON /B110/ CCAP1(10),CCAP2(10)
      COMMON /B120/ DIVIDE(10),TOP(10)
      COMMON /B130/ CSTORE(10),EVAP(10),PREV(10)
      COMMON /B140/ WATERM(10),WATERD(10),WATERP(10),WATERG(10)
      COMMON /B150/ XBAR21(10),STD21(10),PROB(150)
      COMMON /B160/ INDEXR(150),INDEXN(150),INDEXP(150),JOBJ
      COMMON /B170/ DIVIDE1(10)
      COMMON /B180/ CERATEA(10,10),CERATEB(10,10),CCAPA(10,10)
      COMMON /B190/ CCAPB(10,10),IELINE(10),ICLINE(10)
      COMMON /B200/ SERATE(10,10),SCAP(10,10),IFLAG,JFLAG
      CHARACTER MONTH1*10,MONTH2*10,ANS*3,YES*3,NO*3,MONTH*10
      CHARACTER*1 EQUALS,E,B,G,L
      CHARACTER*3 SIGN,POS,NEG,END
      CHARACTER*10 PRIORITY
      CHARACTER*4 ANAME,MNTH,ROWS,OBJT,DAT1,RGHT,PRIO
      CHARACTER*4 GELC,CELC
      CHARACTER*4 FLCN,MIWS,DFWS,RECL,CONS
      CHARACTER*4 INDEXN,INDEXP
      CHARACTER*10 DECEMBER
      DATA MNTH/'MNTH'/,ROWS/'ROWS'/,OBJT/'OBJT'/,DAT1/'DAT1'/
      DATA RGHT/'RGHT'/,PRIO/'PRIO'/
      DATA YES/'YES'/,NO/'NO'/
      DATA GELC/'GELC'/,CELC/'CELC'/
      DATA FLCN/'FLCN'/,MIWS/'MIWS'/,DFWS/'DFWS'/,RECL/'RECL'/
      DATA CONS/'CONS'/,RNOR/'RNOR'/
      DATA END/'END'/
      DATA POS/'POS'/,NEG/'NEG'/
      DATA E/'E'/,B/'B'/,G/'G'/,L/'L'/
```

```
      DATA DECEMBER/'DECEMBER'/
C
C     INPUT THE MONTH TO BE CONSIDERED AND THE NUMBER OF
C     RESERVOIRS IN THE SYSTEM.
C
      WRITE(6,10)
   10 FORMAT(' ENTER THE PREVIOUS MONTH OF OPERATION:')
      READ(5,11) MONTH1
   11 FORMAT(A10)
      WRITE(6,20)
   20 FORMAT(' ENTER THE CURRENT MONTH OF OPERATION:')
      READ(5,11) MONTH2
      WRITE(6,30)
   30 FORMAT(' ENTER THE NUMBER OF RESERVOIRS IN THE SYSTEM:')
      READ(5,*) NRES
      KCONT=0
C
C     LOOP TO COMPUTE NECESSARY VALUES FOR EACH RESERVOIR
C     IN THE SYSTEM.
C
      JFILE=30
   40 IF(KCONT.EQ.1) MONTH1=MONTH2
      DO 50 II=1,NRES
      IF(MONTH1.EQ.DECEMBER) JFLAG=1
      SUMXY=0.00
      IFILE=II+10
      DIVIDE(II)=0.00
      DIVIDE1(II)=0.00
      TOP(II)=0.00
C
C     CALL SUBROUTINE CALC TO COMPUTE THE MEANS AND VARIANCES OF
C     PREVIOUS AND CURRENT MONTHS INFLOWS FROM HISTORICAL DATA.
C
      IF(KCONT.EQ.0) GOTO 46
      STD1(II)=STD2(II)
      XBAR1(II)=XBAR2(II)
      PAVEV(II)=CAVEV(II)
      SUMXX1(II)=SUMXX2(II)
      DO 45 I=1,NDATA
      DIFF1(II,I)=DIFF2(II,I)
   45 CONTINUE
      GOTO 47
   46 CALL CALC(IFILE,XBAR1(II),VAR1,DIFF,SUMX1,KCONT
     1,X1,PAVEV(II),MONTH1)
      STD1(II)=SQRT(VAR1)
      SUMXX1(II)=SUMX1
      DO 41 I=1,NDATA
      DIFF1(II,I)=DIFF(I)
   41 CONTINUE
      IFLAG=1
   47 CALL CALC(IFILE,XBAR2(II),VAR2,DIFF,SUMX2,KCONT
     1,X2,CAVEV(II),MONTH2)
```

```
      IFLAG=0
      JFLAG=0
      STD2(II)=SQRT(VAR2)
      SUMXX2(II)=SUMX2
      DO 42 I=1,NDATA
      DIFF2(II,I)=DIFF(I)
   42 CONTINUE
      DO 60 I=1,NDATA
      SUMXY=(DIFF1(II,I)*DIFF2(II,I))+SUMXY
   60 CONTINUE
C
C     COMPUTE COEFFICIENT OF CORRELATION BETWEEN THE TWO MONTHS.
C
      RHO=SUMXY/(SQRT(SUMXX1(II))*SQRT(SUMXX2(II)))
      CORR=RHO**2
      WRITE(JFILE,70) II,MONTH1,MONTH2,RHO
   70 FORMAT(//,6X,' FOR RESERVOIR',I2,' THE COEFFICIENT OF'
     1,' CORRELATION',/,6X,' BETWEEN THE MONTHS OF ',A9,' AND '
     2,A9,/,6X,' IS ',F6.4,//)
      WRITE(6,80)
   80 FORMAT(' ENTER THE ACTUAL VALUE (IF KNOWN) OR FORECASTED')
      WRITE(6,90) II
   90 FORMAT(' VALUE OF PREVIOUS MONTH INFLOW FOR RESERVOIR',I2,
     1/,' (IN CUBIC FEET PER SECOND(CFS)):')
      READ(5,*) PREV(II)
      IF(ICODE.EQ.2) PREV1(II)=DLOG(PREV(II))
      IF(KCONT.EQ.0) GOTO 105
      CSTORE(II)=SLAST(II)-WATERM(II)-WATERP(II)-WATERG(II)-
     1EVAP(II)+(PREV(II)*59.505)
C
C     COMPUTATIONS OF NORMAL AND LOGNORMAL DISTRIBUTIONS.
C
  105 DO 100 I=1,NDATA
      ZCELS2(I)=0.00
      ZCELS21(I)=0.00
  100 CONTINUE
C
C     CALCULATE CONDITIONAL MEAN AND CONDITIONAL VARIANCE.
C
      XBAR21(II)=XBAR2(II)+RHO*(STD2(II)/STD1(II))*(PREV1(II)
     1-XBAR1(II))
      VAR21=VAR2*(1.0-CORR)
      STD21(II)=SQRT(VAR21)
      WRITE(JFILE,110) XBAR21(II),STD21(II)
  110 FORMAT(//,6X,' CONDITIONAL MEAN = ',F10.5,/,6X,
     1' CONDITIONAL STD. DEV. = ',F10.5)
      WRITE(JFILE,120)
  120 FORMAT(///,'   NUMBER',3X,'CURRENT',3X,
     1'NONCONDITIONAL',3X,'CONDITIONAL',/,12X,'INFLOW'
     2,9X,'CDF',13X,'CDF',/)
      DO 130 I=1,NDATA
C
```

```
C     NONCONDITIONAL CDF OF THE CURRENT MONTH INFLOW.
C
      A2=(X2(I)-XBAR2(II))/STD2(II)
      ZCELS2(I)=ERF(A2)
C
C     CONDITIONAL CDF OF THE CURRENT MONTH INFLOW.
C
      A21=(X2(I)-XBAR21(II))/STD21(II)
      ZCELS21(I)=ERF(A21)
      WRITE(JFILE,140) I,DEXP(X2(I)),ZCELS2(I),ZCELS21(I)
  140 FORMAT(3X,I3,3X,F10.2,2X,F10.3,6X,F10.3)
  130 CONTINUE
      WRITE(JFILE,145)
  145 FORMAT(/////)
C
C     CALCULATE MONTHLY NET EVAPORATION.
C
      IF(KCONT.EQ.1) GOTO 48
      EVAP(II)=PAVEV(II)*(CAREA1(II)+CAREA2(II)*SINIT(II))/12.00
      GOTO 50
   48 EVAP(II)=PAVEV(II)*(CAREA1(II)+CAREA2(II)*CSTORE(II))/12.00
   50 CONTINUE
C
C     READ IN VARIOUS DATA FROM THE INPUT FILE FOR GOAL
C     PROGRAMMING COMPUTATIONS.
C
      DO 150 I=1,3
      T(I)=0.00
  150 CONTINUE
      T(4)=1.E-7
      JCOUNT=0
C
C     SEARCH FOR THE CURRENT MONTH INPUT.
C
      IF(KCONT.EQ.1) GOTO 190
  160 READ(20,170) ANAME
  170 FORMAT(A4)
      IF(ANAME.NE.MNTH) GOTO 160
      READ(20,180) ANAME,MONTH
  180 FORMAT(A4,A10)
      IF(MONTH.NE.MONTH2) GOTO 160
      GOTO 200
  190 READ(20,170) ANAME
      READ(20,180) ANAME,MONTH
C
C     READ IN NUMBER OF ROWS.
C
  200 READ(20,210) ANAME,NROW
  210 FORMAT(A4,I3)
      IF(NROW.GT.0) GOTO 230
      WRITE(6,220)
  220 FORMAT(' NUMBER OF ROWS MUST BE GREATER THAN ZERO!')
```

```
      GOTO 1000
C
C     READ IN THE TYPE OF GOAL.
C
  230 IF(NROW.GT.70) GOTO 250
      READ(20,240) ANAME,(EQUALS(I),I=1,NROW)
  240 FORMAT(A4,70A1)
      GOTO 260
  250 READ(20,240) ANAME,(EQUALS(I),I=1,70)
      READ(20,240) ANAME,(EQUALS(I),I=71,NROW)
C
C     READ IN THE TYPE OF DEVIATION, ROW NUMBER, PRIORITY NUMBER,
C     AND ITS ASSOCIATED WEIGHT.
C
  260 JCOUNT=JCOUNT+1
      READ(20,270) ANAME,SIGN(JCOUNT),(RPW(J,JCOUNT),J=1,3)
  270 FORMAT(A4,A3,3F10.2)
      INDEXP(JCOUNT)=ANAME
      IF(SIGN(JCOUNT).EQ.END) GOTO 280
      GOTO 260
  280 JCOUNT1=JCOUNT-1
      JOBJ=JCOUNT1
C
C     COMPUTE THE NUMBER OF PRIORITIES.
C
      NPRT=RPW(2,JCOUNT1)
      IF(NPRT.GT.0) GOTO 300
      WRITE(6,290)
  290 FORMAT(' NUMBER OF PRIORITIES MUST BE GREATER THAN ZERO!')
      GOTO 1000
  300 JCOUNT=0
C
C     READ IN THE COLUMN NUMBER, ROW NUMBER, AND VALUE OF
C     EACH VARIABLE.
C
  310 JCOUNT=JCOUNT+1
      READ(20,320) ANAME,(CRV(J,JCOUNT),J=1,3)
  320 FORMAT(A4,3F10.2)
      IF(CRV(1,JCOUNT).LE.0) GOTO 330
      GOTO 310
  330 JCOUNT2=JCOUNT-1
C
C     COMPUTE THE NUMBER OF VARIABLES.
C
      NVAR=CRV(1,JCOUNT2)
      IF(NVAR.GT.0) GOTO 350
      WRITE(6,340)
  340 FORMAT(' NUMBER OF VARIABLE MUST BE GREATER THAN ZERO!')
      GOTO 1000
C
C     READ THE PRIORITY LIST.
C
```

```
  350 DO 356 J=1,NPRT
      READ(20,357) ANAME,PRIORITY(J)
  357 FORMAT(A4,A10)
  356 CONTINUE
C
C     READ IN THE RIGHT HAND SIDE VALUES.
C
      DO 360 J=1,NROW
      READ(20,370) ANAME,PROB(J),ORHS(J),NORES
  370 FORMAT(A4,F5.2,F15.2,I2)
      INDEXR(J)=NORES
      INDEXN(J)=ANAME
      IF(KCONT.EQ.1) GOTO 358
      CSTORE(NORES)=SINIT(NORES)
  358 SLAST(NORES)=CSTORE(NORES)
      IF(PROB(J).LE.0.) GOTO 363
C
C     COMPUTE THE INVERSE CDF BY CALLING SUBROUTINE MDNRIS.
C
      CALL MDNRIS(PROB(J),YY)
      DINVS=XBAR21(NORES)+(STD21(NORES)*YY)
      IF(ICODE.EQ.2) DINVS=DEXP(DINVS)
      DINVS=59.505*DINVS
      RHS(J)=DINVS-ORHS(J)-EVAP(NORES)+CSTORE(NORES)
      IF(RHS(J).LT.0.00) RHS(J)=0.00
      GOTO 360
  363 IF(ANAME.NE.GELC.AND.ANAME.NE.CELC) GOTO 373
      IF(ANAME.NE.GELC) GOTO 381
      DO 375 K=1,IELINE(NORES)
      IF(CSTORE(NORES).GT.SERATE(NORES,K)) GOTO 375
      CERATE1(NORES)=CERATEA(NORES,K)
      CERATE2(NORES)=CERATEB(NORES,K)
      GOTO 378
  375 CONTINUE
  378 DIVIDE(NORES)=CERATE1(NORES)+CERATE2(NORES)*CSTORE(NORES)
      RHS(J)=ORHS(J)*1000.00/DIVIDE(NORES)
      GOTO 360
  381 DO 376 K=1,ICLINE(NORES)
      IF(CSTORE(NORES).GT.SCAP(NORES,K)) GOTO 376
      CCAP1(NORES)=CCAPA(NORES,K)
      CCAP2(NORES)=CCAPB(NORES,K)
  376 CONTINUE
  371 TOP(NORES)=HOUR(NORES)*(CCAP1(NORES)+CCAP2(NORES)*CSTORE
     1(NORES))
      DIVIDE1(NORES)=CERATE1(NORES)+CERATE2(NORES)*CSTORE(NORES)
      RHS(J)=TOP(NORES)*1000.00/DIVIDE1(NORES)
      GOTO 360
  373 RHS(J)=ORHS(J)
  360 CONTINUE
      IF(MONTH2.EQ.DECEMBER) REWIND 20
C
C     COUNT THE NUMBER OF CONSTRAINTS WITH POSITIVE VARIABLES.
```

```
C
  365 NFLD=0
      DO 377 I=1,NROW
      IF(EQUALS(I).EQ.B.OR.EQUALS(I).EQ.G) NFLD=NFLD+1
  377 CONTINUE
C
C     COMPUTE THE NUMBER OF COLUMNS.
C
      NCOL=NROW+NFLD+NVAR
      IF(NCOL.GT.0) GOTO 390
      WRITE(6,380)
  380 FORMAT(' NUMBER OF COLUMNS MUST BE GREATER THAN ZERO!')
      GOTO 1000
C
C     COMPUTE THE NUMBER OF POSITIVE AND NEGATIVE DEVIATIONS.
C
  390 NUMDEV=NROW+NFLD
C
C     INITIALIZE VARIOUS MATRICES TO BE USED IN THE REVISED
C     SIMPLEX ALGORITHM.
C
      DO 400 J=1,NCOL
      VALX(1,J)=0.00
      VALX(2,J)=0.00
      KCOL(J)=0
      DO 400 I=1,NROW
      C(I,J)=0.00
  400 CONTINUE
      DO 410 I=1,NROW
      KPOS(I)=0
      MBAS(I)=0
  410 CONTINUE
C
C     INITIALIZE OBJECTIVE FUNCTIONS.
C
      NPRT1=NPRT+1
      DO 420 J=1,NCOL
      DO 420 K=1,NPRT1
      RVLX(K,J)=0.00
  420 CONTINUE
      DO 430 I=1,NROW
      VALY(I,1)=0.00
      VALY(I,2)=0.00
  430 CONTINUE
      NFLD=0
      CONST=0.00
C
C     SET UP INITIAL TABLEAU ACCORDING TO THE TYPES OF GOALS.
C     IF THERE IS SYSTEM CONSTRAINTS, TREAT IT AS A GOAL WITH
C     HIGHEST PRIORITY.
C
      DO 500 I=1,NROW
```

```
      IF(EQUALS(I).EQ.E) GOTO 450
      IF(EQUALS(I).EQ.G) GOTO 460
      IF(EQUALS(I).EQ.L) GOTO 470
      IF(EQUALS(I).EQ.B) GOTO 480
      WRITE(6,490)
  490 FORMAT(' CHECK THE EQUATION TYPE, IT MUST BE E,G,L,OR B!')
      GOTO 1000
C
C     NEITHER NEGATIVE NOR POSITIVE DEVIATION IS ALLOWED.
C
  450 VALX(1,I)=1.00
      VALX(2,I)=1.00
      MBAS(I)=I
      CONST=1.00
      GOTO 500
C
C     NEGATIVE DEVIATION IS NOT ALLOWED.
C
  460 NFLD=NFLD+1
      J=NROW+NFLD
      KPOS(I)=J
      MBAS(I)=I
      VALX(1,I)=1.00
      VALX(2,I)=1.00
      CONST=1.00
      GOTO 500
C
C     POSITIVE DEVIATION IS NOT ALLOWED.
C
  470 MBAS(I)=I
      GOTO 500
C
C     BOTH NEGATIVE AND POSITIVE DEVIATIONS ARE ALLOWED.
C
  480 NFLD=NFLD+1
      J=NROW+NFLD
      KPOS(I)=J
      MBAS(I)=I
  500 CONTINUE
C
C     LOOP TO ADJUST THE PRIORITY LEVELS OF VARIOUS GOALS WHEN
C     ONE OR MORE OF SYSTEM CONSTRAINTS ARE PRESENT.
C
      DO 510 ICOUNT=1,JCOUNT1
      IF(RPW(2,ICOUNT).GT.0) GOTO 530
      WRITE(6,520)
  520 FORMAT(' PRIORITY NUMBER MUST BE GREATER THAN ZERO!')
      GOTO 1000
  530 IF(SIGN(ICOUNT).EQ.NEG) GOTO 540
      IF(SIGN(ICOUNT).EQ.POS) GOTO 600
      GOTO 660
  540 I1=RPW(1,ICOUNT)
```

```
      IF(EQUALS(I1).NE.G.OR.EQUALS(I1).NE.E) GOTO 560
      WRITE(6,550)
  550 FORMAT(' NON EXISTENT NEGATIVE DEVIATION!')
      GOTO 1000
  560 IF(CONST-1.0) 570,580,570
C
C     IF THERE IS ONE OR MORE SYSTEM CONSTRAINT, MOVE ALL
C     PRIORITIES IN THE OBJECTIVE FUNCTION DOWN ONE LEVEL.
C
  570 VALX(1,I1)=RPW(2,ICOUNT)
      GOTO 590
  580 VALX(1,I1)=RPW(2,ICOUNT)+1
  590 VALX(2,I1)=RPW(3,ICOUNT)
      GOTO 510
  600 I=RPW(1,ICOUNT)
      IF(KPOS(I).NE.0) GOTO 620
      WRITE(6,610)
  610 FORMAT(' NON EXISTENT POSITIVE DEVIATION!')
  620 IF(CONST-1.0) 630,640,630
  630 VALX(1,KPOS(I))=RPW(2,ICOUNT)
      GOTO 650
  640 VALX(1,KPOS(I))=RPW(2,ICOUNT)+1
  650 VALX(2,KPOS(I))=RPW(3,ICOUNT)
      GOTO 510
  660 IF(RPW(3,ICOUNT)) 670,510,670
  670 WRITE(6,680)
  680 FORMAT(' FAILED TO IDENTIFY AS POSITIVE OR NEGATIVE'
     1,'DEVIATION!')
      GOTO 1000
  510 CONTINUE
C
C     SET UP THE PRIORITIES AND WEIGHTS OF THE BASIS IN THE
C     INITIAL TABLEAU.
C
      DO 690 I=1,NROW
      VALY(I,1)=VALX(1,I)
      VALY(I,2)=VALX(2,I)
  690 CONTINUE
      ICOUNT=0
C
C     FILL IN THE BASIC COLUMNS OF THE INITIAL TABLEAU.
C
      DO 700 J=1,NROW
      ICOUNT=ICOUNT+1
      KCOL(J)=J
      DO 700 I=1,NROW
      IF(MBAS(I).NE.J) GOTO 700
      IRC(ICOUNT)=I
      A(ICOUNT)=1.00
      KL(J)=ICOUNT
      C(I,J)=1.00
  700 CONTINUE
```

```
C
C     FILL IN THE POSITIVE DEVIATION COLUMNS OF THE INITIAL TABLEAU
C     (OPPOSITE SIGN OF CORRESPONDING NEGATIVE-DEVIATION COLUMNS).
C
      DO 710 J=1,NFLD
      ICOUNT=ICOUNT+1
      DO 710 I=1,NROW
      JJ=NROW+J
      IF(KPOS(I).NE.JJ) GOTO 710
      IRC(ICOUNT)=I
      A(ICOUNT)=-1.00
      KL(JJ)=ICOUNT
      C(I,JJ)=-1.00
  710 CONTINUE
C
C     LIST COEFFICIENTS OF ALL DECISION VARIABLES.
C
      JJ=NUMDEV
      DO 720 ICOUNT1=1,JCOUNT2
      ICOUNT=ICOUNT+1
      I1=NUMDEV+CRV(1,ICOUNT1)
      IF(I1.EQ.JJ) GOTO 730
      JJ=JJ+1
      KL(JJ)=ICOUNT
  730 IRC(ICOUNT)=CRV(2,ICOUNT1)
      A(ICOUNT)=CRV(3,ICOUNT1)
  720 CONTINUE
      KL(JJ+1)=ICOUNT+1
C
C     FILL IN THE RIGHT HAND SIDE VALUES OF THE INITIAL TABLEAU.
C
      DO 740 I=1,NROW
      IF(RHS(I)) 750,770,780
  750 WRITE(6,760)
  760 FORMAT(' RIGHT HAND SIDE CANNOT BE NEGATIVE!')
      GOTO 1000
  770 RHS(I)=1.D-10
  780 RHS1(I)=RHS(I)
  740 CONTINUE
C
C     INITIALIZE INDEX VARIABLES.
C
      NONZERO(1)=1
      MTRANS=0
      ZMAX=0.00
      COMPARE=0.00
      IF(CONST-1.00) 800,790,800
  790 LPRT=NPRT+1
      GOTO 810
  800 LPRT=NPRT
C
C     MAIN LOOP TO PERFORM THE REVISED SIMPLEX ALGORITHM FOR
```

```
C     EACH PRIORITY LEVEL.
C
  810 DO 820 K=1,LPRT
      DD=0.00
C
C     FIND THE LARGEST WEIGHT ASSOCIATED WITH THE CURRENT PRIORITY.
C
  830 DO 840 I=1,NROW
      IF(VALY(I,1)-K) 840,850,840
  850 COMPARE=1.00
      IF(VALY(I,2)-DD) 840,840,860
  860 DD=VALY(I,2)
  840 CONTINUE
      IF(COMPARE) 820,820,870
C
C     IDENTIFY THE PIVOTED COLUMN BY CALLING SUBROUTINE COLUMN.
C
  870 CALL COLUMN(ZMAX,K,JCOL,DD)
      IF(ZMAX) 820,820,880
C
C     IDENTIFY THE PIVOTED ROW BY CALLING SUBROUTINE ROW.
C
  880 CALL ROW(JCOL,IROW)
      IF(IROW.EQ.0) GOTO 820
C
C     REPLACE OLD BASIC VARIABLE BY NEW BASIC VARIABLE.
C
      IPC=MBAS(IROW)
      KCOL(JCOL)=IROW
      MBAS(IROW)=JCOL
      IF(CONST-1.0) 900,890,900
  890 IF(VALY(IROW,1)-1.00) 900,910,900
  900 KCOL(IPC)=0
  910 VALY(IROW,1)=VALX(1,JCOL)
      VALY(IROW,2)=VALX(2,JCOL)
C
C     CALL SUBROUTINE UPDATE TO COMPUTE THE NEW TABLEAU.
C
      CALL UPDATE(IROW)
C
C     REINITIALIZE INDEX VARIABLES.
C
      ZMAX=0.00
      IROW=0
      JCOL=0
      COMPARE=0.00
      GOTO 830
  820 CONTINUE
C
C     CALL SUBROUTINE OUTPUT TO PRINT OUT RESULTS.
C
      IFILE=6
```

```
      CALL OUTPUT(IFILE,NRES,MONTH2,PRIORITY)
      WRITE(6,920)
  920 FORMAT(///,' IS THE SOLUTION OBTAINED SATISFACTORY?')
      WRITE(6,930)
  930 FORMAT(' (ENTER "YES" OR "NO"):')
      READ(5,931) ANS
  931 FORMAT(A3)
      IF(ANS.EQ.NO) GOTO 980
      WRITE(6,960)
  960 FORMAT(///,' THE RESULTS FOR THIS MONTH ARE PROVIDED IN ',
     1'THE OUTPUT FILE')
      IFILE=31
      CALL OUTPUT(IFILE,NRES,MONTH2,PRIORITY)
      WRITE(6,940)
  940 FORMAT(///,' DO YOU WANT TO CONTINUE TO THE NEXT MONTH?')
      WRITE(6,950)
  950 FORMAT(' (ENTER "YES" OR "NO"):')
      READ(5,931) ANS
      IF(ANS.EQ.NO) GOTO 961
      KCONT=1
      GOTO 40
  961 WRITE(6,970)
  970 FORMAT(///,' SESSION COMPLETED'//)
      GOTO 1100
C
C     CALL SUBROUTINE CHANGE TO MODIFY THE PRIORITY STRUCTURE.
C
  980 CALL CHANGE(NRES,PRIORITY)
      GOTO 365
 1000 WRITE(6,1010)
 1010 FORMAT(///,' PROGRAM ENDED IN AN ERROR STATE'//)
 1100 STOP
      END
C
C
C
C*************************************************************C
C                                                             C
C                    SUBROUTINE CALC                          C
C                    ===============                          C
C                                                             C
C          THIS SUBROUTINE IS CALLED BY THE MAIN ROUTINE.     C
C   IT READS THE DATA FROM THE RESERVOIR CHARACTERISTIC       C
C   FILE FOR EACH RESERVOIR IN THE SYSTEM. THE HISTORICAL     C
C   INFLOW DATA ARE THEN PRINTED OUT. FOR INFLOWS WHICH       C
C   FOLLOW LOGNORMAL DISTRIBUTION, THEY ARE CONVERTED TO      C
C   THEIR LOGARITHMS. THE MEAN AND VARIANCE OF EACH MONTH     C
C   INFLOW ARE ALSO COMPUTED IN THIS SUBROUTINE.              C
C                                                             C
C*************************************************************C
C
C
```

```
C
      SUBROUTINE CALC(IFILE,XMEAN,VAR,DIFF,SUMXX,KCONT,Y,AVEV,
     1MONTHI)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION X(100),Y(100),DIFF(100)
      COMMON /B90/ NDATA,ICODE,II,SINIT(10),HOUR(10),SLAST(10)
      COMMON /B100/ CAREA1(10),CAREA2(10),CERATE1(10),CERATE2(10)
      COMMON /B110/ CCAP1(10),CCAP2(10)
      COMMON /B180/ CERATEA(10,10),CERATEB(10,10),CCAPA(10,10)
      COMMON /B190/ CCAPB(10,10),IELINE(10),ICLINE(10)
      COMMON /B200/ SERATE(10,10),SCAP(10,10),IFLAG,JFLAG
      CHARACTER*10 DECEMBER
      CHARACTER*10 MONTH,MONTHI
      DATA DECEMBER/'DECEMBER'/
C
C
C
      JFILE=30
      SUMX=0.00
      SUMXX=0.00
C
C     READ IN DATA.
C
      IF(JFLAG.EQ.1) GOTO 5
      IF(KCONT.EQ.1.OR.IFLAG.EQ.1) GOTO 85
    5 READ(IFILE,10) NDATA,ICODE
   10 FORMAT(I3,I2)
      READ(IFILE,21) CAREA1(II),CAREA2(II)
   21 FORMAT(F10.2,F10.7)
      READ(IFILE,22) IELINE(II),ICLINE(II)
   22 FORMAT(2I2)
      DO 23 K=1,IELINE(II)
      READ(IFILE,25) CERATEA(II,K),CERATEB(II,K),SERATE(II,K)
   25 FORMAT(F10.2,F10.7,F10.2)
   23 CONTINUE
      DO 24 K=1,ICLINE(II)
      READ(IFILE,25) CCAPA(II,K),CCAPB(II,K),SCAP(II,K)
   24 CONTINUE
      IF(JFLAG.EQ.1.AND.KCONT.EQ.1) GOTO 85
   30 READ(IFILE,40) MONTH,AVEV,SINIT(II),HOUR(II)
   40 FORMAT(A10,F5.2,F10.2,F6.2)
      IF(MONTH.EQ.MONTHI) GOTO 95
      DO 60 I=1,NDATA
      READ(IFILE,70) X(I)
   60 CONTINUE
      GOTO 30
   85 READ(IFILE,40) MONTH,AVEV,SINIT(II),HOUR(II)
      MONTHI=MONTH
   95 DO 65 I=1,NDATA
      READ(IFILE,70) X(I)
   70 FORMAT(F10.3)
      Y(I)=X(I)
```

```
   65 CONTINUE
C
C     PRINT OUT ORIGINAL DATA.
C
      WRITE(JFILE,80) MONTH,II
   80 FORMAT('   FOR THE MONTH OF ',A9,'(RESERVOIR',I2,')')
      WRITE(JFILE,81)
   81 FORMAT('   =======================================')
      WRITE(JFILE,90) (X(I),I=1,NDATA)
   90 FORMAT(//,'      OBSERVED DATA; ',//,(5X,5(F10.2,1X)))
C
C     SORT DATA IN ASCENDING ORDER.
C
      DO 100 K=1,NDATA
      DO 100 L=K,NDATA
      IF (Y(K).GT.Y(L)) GOTO 110
      GOTO 100
  110 AA=Y(K)
      Y(K)=Y(L)
      Y(L)=AA
  100 CONTINUE
      WRITE(JFILE,120) (Y(I),I=1,NDATA)
  120 FORMAT(///,'      OBSERVED DATA IN ASCENDING ORDER: ',//,
     1(5X,5(F10.2,1X)))
C
C     LOG-TRANSFORMED DATA FOR LOGNORMAL DISTRIBUTION.
C
      IF(ICODE.NE.2) GOTO 150
      DO 130 I=1,NDATA
      X(I)=DLOG(X(I))
      Y(I)=DLOG(Y(I))
  130 CONTINUE
      WRITE(JFILE,140) (Y(I),I=1,NDATA)
  140 FORMAT(///,'      LOG-TRANSFORMED DATA IN ASCENDING ORDER:',
     1//,(5X,5(F10.2,1X)))
C
C     CALCULATE MEAN AND VARIANCE.
C
  150 DO 160 I=1,NDATA
      SUMX=X(I)+SUMX
  160 CONTINUE
      XMEAN=SUMX/NDATA
      DO 170 I=1,NDATA
      SUMXX=(X(I)-XMEAN)**2+SUMXX
      DIFF(I)=X(I)-XMEAN
  170 CONTINUE
      VAR=SUMXX/(NDATA-1.00)
      WRITE(JFILE,180) XMEAN,VAR
  180 FORMAT(//,10X,' MEAN = ',F10.5,5X,' VARIANCE = ',F10.5,//)
      IF(MONTH.EQ.DECEMBER) REWIND IFILE
      RETURN
      END
```

```
C
C
C
C*************************************************************C
C                                                             C
C                      FUNCTION ERF                           C
C                      ============                           C
C                                                             C
C          THIS FUNCTION IS CALLED BY THE MAIN ROUTINE.       C
C   IT COMPUTES THE NORMAL DISTRIBUTION FUNCTION. THE         C
C   APPROXIMATION OBTAINED FROM THIS FUNCTION GIVES THE       C
C   MAXIMUM ERROR OF 0.0000003.                               C
C                                                             C
C          FOR MORE DETAILS, REFER TO PHILLIPS(1972).         C
C                                                             C
C*************************************************************C
C
C
C
      FUNCTION ERF(Z)
      IF(Z.GT.4.17) GOTO 104
      IF(Z.LT.-4.17) GOTO 105
      ZZ=Z
      IF(Z.LT.0.0) ZZ=-Z
      T=ZZ/1.4142142
      D=((((((.430638E-4*T+.2765672E-3)*T+.1520143E-3)*T
     1+.92705272E-2)*T+.42282012E-1)*T+.70523078E-1)*T+1.0)**2
      D=D*D
      D=D*D
      D=D*D
      ERF=.5-.5/D
      IF(Z) 101,102,103
  101 ERF=.5-ERF
      GOTO 106
  102 ERF=.5
      GOTO 106
  103 ERF=.5+ERF
      GOTO 106
  104 ERF=1.0
      RETURN
  105 ERF=0.0
  106 CONTINUE
      RETURN
      END
C
C
C
C******************************************************************C
C                                                                  C
C                     SUBROUTINE MDNRIS                            C
C                     ================                             C
C                                                                  C
```

```
C          THIS SUBROUTINE IS CALLED BY THE MAIN ROUTINE. IT    C
C   COMPUTES THE INVERSE STANDARD NORMAL (GAUSSIAN) PROBABI-    C
C   LITY FUNCTION. IT IS ADAPTED FROM THE IMSL ROUTINE.         C
C                                                               C
C          'P' IS THE PROBABILITY VALUE IN THE RANGE (0.0,1.0)  C
C   TO BE PROVIDED. 'Y' IS THE OUTPUT FROM THIS ROUTINE.        C
C                                                               C
C***************************************************************C
C
C
C
      SUBROUTINE MDNRIS(P,Y)
      REAL P,Y,EPS,G0,G1,G2,G3,H0,H1,H2,A,W,WI,SN,SD
      REAL SQRT2,X,XINF
      DATA XINF/Z7FFFFFFF/,SQRT2/1.414214/,EPS/Z3C100000/
      DATA G0/.1851159E-3/,G1/-.2028152E-2/,G2/-.1498384/
      DATA G3/.1078639E-1/,H0/.9952975E-1/,H1/.5211733/
      DATA H2/-.6888301E-1/
C
C
C
      IF(P.LE.EPS) GOTO 10
      X=1.0-(P+P)
      CALL MERFI(X,Y)
      Y=-SQRT2*Y
      GOTO 20
   10 A=P+P
      W=SQRT(-ALOG(A+(A-A*A)))
      WI=1./W
      SN=((G3*WI+G2)*WI+G1)*WI
      SD=((WI+H2)*WI+H1)*WI+H0
      Y=W+W*(G0+SN/SD)
      Y=-Y*SQRT2
   20 RETURN
      END
C
C
C
C*****************************************************************C
C                                                                 C
C                        SUBROUTINE MERFI                         C
C                        ================                         C
C                                                                 C
C          THIS SUBROUTINE IS CALLED BY SUBROUTINE MDNRIS. IT     C
C   PERFORMS NECESSARY COMPUTATIONS OF THE INVERSE STANDARD       C
C   NORMAL PROBABILITY FUNCTION APPROXIMATIONS. THE MINIMAX       C
C   RATIONAL FUNCTION IS USE AS THE APPROXIMATION ROUTINE.        C
C                                                                 C
C*****************************************************************C
C
C
C
```

```
      SUBROUTINE MERFI(P,Y)
      REAL P,Y,A,B,X,Z,W,WI,SN,SD,F,Z2,RINFM,A1,A2,A3,B0,B1,B2
      REAL B3,C0,C1,C2,C3,D0,D1,D2,E0,E1,E2,E3,F0,F1,F2
      REAL G0,G1,G2,G3,H0,H1,H2,SIGMA
      DATA A1/-.5751703/,A2/-1.896513/,A3/-.5496261E-1/
      DATA B0/-.1137730/,B1/-3.293474/,B2/-2.374996/
      DATA B3/-1.187515/,C0/-.1146666/,C1/-.1314774/
      DATA C2/-.2368201/,C3/.5073975E-1/,D0/-44.27977/
      DATA D1/21.98546/,D2/-7.586103/,E0/-.5668422E-1/
      DATA E1/.3937021/,E2/-.3166501/,E3/.6208963E-1/
      DATA F0/-6.266786/,F1/4.666263/,F2/-2.962883/
      DATA G0/.1851159E-3/,G1/-.2028152E-2/,G2/-.1498384/
      DATA G3/.1078639E-1/,H0/.9952975E-1/,H1/.5211733/
      DATA H2/-.6888301E-1/,RINFM/Z7FFFFFFF/
C
C
C
      X=P
      SIGMA=SIGN(1.0,X)
      Z=ABS(X)
      IF(Z.LE.85) GOTO 20
      A=1.-Z
      B=Z
    5 W=SQRT(-ALOG(A+A*B))
      IF(W.LT.2.5) GOTO 15
      IF(W.LT.4.) GOTO 10
      WI=1./W
      SN=((G3*WI+G2)*WI+G1)*WI
      SD=((WI+H2)*WI+H1)*WI+H0
      F=W+W*(G0+SN/SD)
      GOTO 25
   10 SN=((E3*W+E2)*W+E1)*W
      SD=((W+F2)*W+F1)*W+F0
      F=W+W*(E0+SN/SD)
      GOTO 25
   15 SN=((C3*W+C2)*W+C1)*W
      SD=((W+D2)*W+D1)*W+D0
      F=W+W*(C0+SN/SD)
      GOTO 25
   20 Z2=Z*Z
      F=Z+Z*(B0+A1*Z2/(B1+Z2+A2/(B2+Z2+A3/(B3+Z2))))
   25 Y=SIGMA*F
      RETURN
      END
C
C
C
C***********************************************************C
C                                                           C
C                 SUBROUTINE COLUMN                         C
C                 =================                         C
C                                                           C
```

```
C          THIS SUBROUTINE IS CALLED BY THE MAIN ROUTINE.   C
C   IT IDENTIFIES THE PIVOTED COLUMN ACCORDING TO THE       C
C   SIMPLEX METHOD. THAT IS, THE COLUMN WITH THE LARGEST    C
C   Z-C VALUE. CHECKS ARE MADE TO AVOID COMPUTATIONS OF     C
C   Z-C VALUES FROM COLUMNS WHICH CANNOT BE PIVOTED. A      C
C   COLUMN CANNOT BE PIVOTED IF:                            C
C                                                           C
C          1. IT IS ALREADY A BASIC COLUMN, OR              C
C          2. IT LEADS TO DEGRADATION IN ANY OF THE         C
C             HIGHER PRIORITY GOALS.                        C
C                                                           C
C***********************************************************C
C
C
C
      SUBROUTINE COLUMN(ZMAX,K,JCOL,DD)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /B30/ NCOL,A(3500),KCOL(350),Y(150),VALX(2,350),LPRT
      COMMON /B40/ T(4),RHS1(150),X(150),NROW,VALY(150,2)
      COMMON /B50/ EE(10000),IP(500),NONZERO(250)
      COMMON /B60/ IE(10000),IRC(3500),KL(350),MTRANS
C
C     LOOP FOR EACH COLUMN.
C
      DO 10 J=1,NCOL
C
C     CHECK IF THE COLUMN IS BASIC COLUMN.
C
      IF(KCOL(J)) 10,20,10
C
C     CHECK IF THE VARIABLE UNDER THE COLUMN HAS ASSOCIATED
C     PRIORITY OF ANY LEVEL.
C
   20 IF(VALX(1,J)-0.00) 50,50,30
C
C     CHECK IF THE VARIABLE UNDER THE COLUMN HAS ASSOCIATED
C     PRIORITY OF HIGHER LEVEL.
C
   30 IF(VALX(1,J)-K) 10,40,50
C
C     CHECK IF THE VARIABLE UNDER THE COLUMN HAS HIGHER WEIGHT
C     OF SAME PRIORITY.
C
   40 IF(VALX(2,J)-DD) 50,10,10
C
C     INITIALIZE NEW BASIC COLUMN.
C
   50 DO 60 I=1,NROW
      Y(I)=0.00
   60 CONTINUE
C
C     DERIVE ORIGINAL COEFFICIENTS.
```

```
C
      LUMP=KL(J)
      LUMP1=KL(J+1)-1
      DO 70 KK=LUMP,LUMP1
      IMP=IRC(KK)
      Y(IMP)=A(KK)
   70 CONTINUE
      IF(MTRANS) 120,120,80
C
C     COMPUTE THE COEFFICIENTS USING THE ORIGINAL COEFFICIENTS
C     AND THE TRANSFORMED COLUMNS.
C
   80 DO 90 I=1,MTRANS
      D=Y(IP(I))
      Y(IP(I))=0.00
      IF(DABS(D)-T(4)) 90,90,100
  100 LUMP2=NONZERO(I)
      LUMP3=NONZERO(I+1)-1
      DO 110 KK=LUMP2,LUMP3
      II=IE(KK)
      Y(II)=Y(II)+EE(KK)*D
  110 CONTINUE
   90 CONTINUE
  120 ZJ=0.00
      DO 130 I=1,NROW
      IF(VALY(I,1)-K) 130,140,130
  140 ZJ=ZJ+VALY(I,2)*Y(I)
  130 CONTINUE
  150 IF(ZJ-T(4)) 10,10,160
  160 IF(MTRANS) 240,240,170
  170 IF(VALX(1,J)-0.00) 180,180,230
  180 IF(K-LPRT) 190,190,230
  190 IPROTY=K-1
      DO 200 KK=1,IPROTY
      SUMP=0.00
      DO 210 I=1,NROW
      IF(VALY(I,1)-KK) 210,220,210
  220 P=VALY(I,2)*Y(I)
      SUMP=SUMP+P
  210 CONTINUE
      IF(SUMP) 10,200,200
  200 CONTINUE
  230 IF(ZJ-ZMAX) 10,10,250
  240 IF(ZJ-ZMAX) 10,250,250
  250 ZMAX=ZJ
      JCOL=J
      DO 260 I=1,NROW
      X(I)=Y(I)
  260 CONTINUE
   10 CONTINUE
      RETURN
      END
```

```
C
C
C
C******************************************************************C
C                                                                  C
C                     SUBROUTINE ROW                               C
C                     ==============                               C
C                                                                  C
C           THIS SUBROUTINE IS CALLED BY THE MAIN ROUTINE.         C
C    IT IDENTIFIES THE PIVOTED ROW BY COMPARING THE RATIOS         C
C    OF THE RIGHT HAND SIDES AND THE RESPECTIVE ELEMENTS OF        C
C    THE PIVOTED COLUMN. THE SMALLEST RATIO IS CHOSEN.             C
C                                                                  C
C******************************************************************C
C
C
C
      SUBROUTINE ROW(JCOL,IROW)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /B40/ T(4),RHS1(150),X(150),NROW,VALY(150,2)
C
C     INITIALIZATION.
C
      AA=1.0E+20
      PP=0.00
      WW=0.00
      DO 10 I=1,NROW
      IF(X(I)-T(4)) 10,10,20
C
C     APPLY THE MINIMUM RATIO RULE.
C
   20 RATIO=RHS1(I)/X(I)
      IF(RATIO-AA) 50,30,10
   30 IF(PP-VALY(I,1)) 10,40,50
   40 IF(WW-VALY(I,2)) 50,10,10
   50 AA=RATIO
      IROW=I
      PP=VALY(IROW,1)
      WW=VALY(IROW,2)
   10 CONTINUE
      RETURN
      END
C
C
C
C******************************************************************C
C                                                                  C
C                     SUBROUTINE UPDATE                            C
C                     =================                            C
C                                                                  C
C           THIS SUBROUTINE IS CALLED BY THE MAIN ROUTINE. IT      C
C    COMPUTES A NEW SOLUTION AND ADD A NEW TRANSFORMED VECTOR      C
```

```
C   TO THE INVERSE, USING THE PRODUCT FORM OF THE INVERSE.        C
C                                                                 C
C*****************************************************************C
C
C
C
      SUBROUTINE UPDATE(IROW)
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON /B40/ T(4),RHS1(150),X(150),NROW,VALY(150,2)
      COMMON /B50/ EE(10000),IP(500),NONZERO(250)
      COMMON /B60/ IE(10000),IRC(3500),KL(350),MTRANS
C
C     INITIALIZATION.
C
      T(1)=X(IROW)
      T(2)=RHS1(IROW)/T(1)
      T(3)=DABS(T(4)*T(1))
      RHS1(IROW)=0.00
      X(IROW)=-1.00
      K=NONZERO(MTRANS+1)
      DO 10 I=1,NROW
      IF(DABS(X(I))-T(3)) 10,10,20
C
C     COMPUTE NEW RIGHT HAND SIDE VALUES.
C
   20 RHS1(I)=RHS1(I)-T(2)*X(I)
C
C     COMPUTE AN ETA VECTOR.
C
      EE(K)=-X(I)/T(1)
      IE(K)=I
      K=K+1
   10 CONTINUE
      MTRANS=MTRANS+1
      IP(MTRANS)=IROW
      NONZERO(MTRANS+1)=K
      RETURN
      END
C
C
C
C****************************************************************C
C                                                                C
C                    SUBROUTINE OUTPUT                           C
C                    =================                           C
C                                                                C
C         THIS SUBROUTINE IS CALLED BY THE MAIN ROUTINE. IT      C
C   DISPLAYS THE FOLLOWING RESULTS:                              C
C                                                                C
C         1. LAST PERIOD STORAGE OF EACH RESERVOIR               C
C         2. ANALYSIS OF DEVIATIONS FROM TARGET VALUES           C
C         3. AMOUNT OF RELEASE FROM EACH RESERVOIR               C
```

```
C          4. ANALYSIS OF PRIORITY STRUCTURE.                          C
C                                                                      C
C          THE FORMATS OF ITEMS 2 AND 3 ARE APPROPRIATE TO             C
C   THE THREE-RESERVOIR SYSTEM ANALYZED IN THIS RESEARCH.              C
C   MODIFICATIONS NEED TO BE MADE FOR OTHER SYSTEMS.                   C
C                                                                      C
C**********************************************************************C
C
C
C
      SUBROUTINE OUTPUT(IFILE,NRES,MONTH2,PRIORITY)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION EXCESS(150),SHORT(150)
      DIMENSION PRIORITY(15)
      COMMON /B10/ NVAR,NPRT,NUMDEV,RVLX(15,350),KPOS(150),MBAS(350)
      COMMON /B20/ C(150,350),ZVAL(15),CONST
      COMMON /B40/ T(4),RHS1(150),X(150),NROW,VALY(150,2)
      COMMON /B70/ SIGN(150),EQUALS(150)
      COMMON /B80/ CRV(3,2451),RPW(3,141),RHS(150),ORHS(150)
      COMMON /B90/ NDATA,ICODE,II,SINIT(10),HOUR(10),SLAST(10)
      COMMON /B120/ DIVIDE(10),TOP(10)
      COMMON /B130/ CSTORE(10),EVAP(10),PREV(10)
      COMMON /B140/ WATERM(10),WATERD(10),WATERP(10),WATERG(10)
      COMMON /B160/ INDEXR(150),INDEXN(150),INDEXP(150),JOBJ
      CHARACTER MONTH2*10
      CHARACTER*10 PRIORITY
      CHARACTER*4 INDEXN,INDEXP
      CHARACTER*4 GELC,CELC
      DATA GELC/'GELC'/,CELC/'CELC'/
C
C     DISPLAY VALUES FOR VARIOUS GOALS.
C
      IF(IFILE.EQ.31) GOTO 20
      WRITE(IFILE,10)
   10 FORMAT(//,' THE RESULTS FROM THIS RUN ARE AS FOLLOWS:')
      WRITE(IFILE,12)
   12 FORMAT(' =========================================')

      GOTO 35
   20 WRITE(IFILE,30) MONTH2
   30 FORMAT(//,' FOR THE MONTH OF ',A9,
     1',THE RESULTS ARE AS FOLLOWS:')
      WRITE(IFILE,31)
   31 FORMAT(' ============================================',
     1'=========')
   35 DO 36 I=1,NRES
      WRITE(IFILE,37) I,PREV(I)*59.505,CSTORE(I)
   37 FORMAT(//,'  FOR RESERVOIR NUMBER',I2,':',/,
     1'     THE PREVIOUS PERIOD INFLOW(AC-FT) IS',F15.2,/,
     2'     THE PREVIOUS PERIOD RESERVOIR STORAGE (AC-FT) IS'
     3,F15.2)
   36 CONTINUE
```

```
 40 WRITE(IFILE,50)
 50 FORMAT(//,'   (1). ANALYSIS OF DEVIATIONS FROM TARGET AMOUNTS
   1')
    WRITE(IFILE,60)
 60 FORMAT(//,16X,' PURPOSE',14X,' TARGET',2X,' ACTUAL',1X,
   1' POSITIVE',2X,' NEGATIVE')
    WRITE(IFILE,70)
 70 FORMAT(38X,' AMOUNT',2X,' AMOUNT',1X,' DEVIATION',2X,
   1'DEVIATION')
    DO 80 I=1,NROW
    SHORT(I)=0.00
    EXCESS(I)=0.00
 80 CONTINUE
    DO 120 I=1,NROW
    DO 90 J=1,NROW
    IF(MBAS(J).EQ.KPOS(I)) GOTO 110
    IF(MBAS(J).EQ.I) GOTO 100
 90 CONTINUE
    GOTO 120
100 SHORT(I)=RHS1(J)
    GOTO 120
110 EXCESS(I)=RHS1(J)
120 CONTINUE
    WRITE(IFILE,130)
130 FORMAT(/,' RELEASE FOR M&I WATER SUPPLY(AC-FT):',/)
    DO 140 I=1,NRES
    WATERM(I)=RHS(I)-SHORT(I)+EXCESS(I)
    WRITE(IFILE,150) I,ORHS(I),WATERM(I),EXCESS(I),SHORT(I)
150 FORMAT(10X,' RESERVOIR NO.',I2,6X,' => ',F9.2,3F10.2)
140 CONTINUE
    INCRE1=NRES+1
    INCRE2=2*NRES
    WRITE(IFILE,160)
160 FORMAT(/,' RELEASE FOR DOWNSTREAM FLOW(AC-FT):',/)
    DO 170 I=INCRE1,INCRE2
    J=I-NRES
    WATERD(J)=RHS(I)-SHORT(I)+EXCESS(I)
    WRITE(IFILE,150) J,ORHS(I),WATERD(J),EXCESS(I),SHORT(I)
170 CONTINUE
    WRITE(IFILE,180)
180 FORMAT(/,' HYDROPOWER GENERATION(MWH):',/)
    INCRE1=INCRE2+1
    INCRE2=3*NRES
    DO 190 I=INCRE1,INCRE2
    J=I-2*NRES
    WATERP(J)=RHS(I)-SHORT(I)+EXCESS(I)
    IF(INDEXN(I).EQ.GELC) GOTO 185
    EXCESS(I)=0.00
    SHORT(I)=0.00
    ACTUAL=0.00
    RIGHT=0.00
    GOTO 186
```

```
185 ACTUAL=(WATERP(J)*DIVIDE(J))/1000000.00
    RIGHT=ORHS(I)/1000.00
186 WRITE(IFILE,150) J,RIGHT,ACTUAL
   1,EXCESS(I)/1000000.00,SHORT(I)/1000000.00
190 CONTINUE
    IF(IFILE.EQ.31) GOTO 198
    DO 195 I=1,NRES
    WATERG(I)=WATERD(I)-WATERP(I)
195 CONTINUE
198 WRITE(IFILE,200)
200 FORMAT(/,' RELEASE FOR FLOOD CONTROL(AC-FT):',/)
    INCRE1=INCRE2+1
    INCRE2=4*NRES
    DO 210 I=INCRE1,INCRE2
    J=I-3*NRES
    ACTUAL=WATERM(J)+WATERP(J)+WATERG(J)
    WRITE(IFILE,220) J,RHS(I),ACTUAL,EXCESS(I),SHORT(I)
220 FORMAT(10X,' RESERVOIR NO.',I2,6X,' => ',F9.2,3F10.2)
210 CONTINUE
    WRITE(IFILE,230)
230 FORMAT(/,' RELEASE FOR RECREATION(AC-FT):',/)
    INCRE1=INCRE2+1
    INCRE2=5*NRES
    DO 240 I=INCRE1,INCRE2
    J=I-4*NRES
    ACTUAL=WATERM(J)+WATERP(J)+WATERG(J)
    WRITE(IFILE,250) J,RHS(I),ACTUAL,EXCESS(I),SHORT(I)
250 FORMAT(10X,' RESERVOIR NO.',I2,6X,' <= ',F9.2,3F10.2)
240 CONTINUE
    WRITE(IFILE,260)
260 FORMAT(///,'     (2). RELEASES FROM RESERVOIRS(AC-FT)')
    WRITE(IFILE,270)
270 FORMAT(//,37X,' RESERVOIR 1',2X,' RESERVOIR 2',2X,
   1' RESERVOIR 3')
    WRITE(IFILE,280) (WATERP(I),I=1,NRES)
280 FORMAT(/,10X,' NORMAL RELEASE(FOR POWER',3X,F10.2,3X
   1,F10.2,3X,F11.2)
    WRITE(IFILE,290)
290 FORMAT(10X,' OR NON POWER GENERATION)')
    WRITE(IFILE,300) (WATERM(I),I=1,NRES)
300 FORMAT(/,10X,' RELEASE FOR M&I WATER',6X,F10.2,3X,F10.2,3X,
   1F11.2)
    WRITE(IFILE,310)
310 FORMAT(10X,' SUPPLY')
    WRITE(IFILE,320) (WATERG(I),I=1,NRES)
320 FORMAT(/,10X,' RELEASE THROUGH SPILLWAY',3X,F10.2,3X,F10.2,
   13X,F11.2)
    DO 330 K=1,NPRT
    ZVAL(K)=0.00
    DO 340 I=1,NROW
    IF(VALY(I,1)-K) 340,350,340
350 ZVAL(K)=ZVAL(K)+VALY(I,2)*RHS1(I)
```

```
  340 CONTINUE
  330 CONTINUE
      WRITE(IFILE,360)
  360 FORMAT(///,'    (3). ANALYSIS OF PRIORITY STRUCTURE')
      DO 370 K=1,NPRT
      WRITE(IFILE,380) K,PRIORITY(K),ZVAL(K)
  380 FORMAT(/,10X,' PRIORITY',I2,' - ',A10,17X,F10.2)
  370 CONTINUE
      WRITE(IFILE,390)
  390 FORMAT(/////,10X,' FC - FLOOD CONTROL',/,10X,' R - RECREATION'
     1,/,10X, ' P - POWER GENERATION')
      WRITE(IFILE,400)
  400 FORMAT(10X,' M&I - MUNICIPAL AND INDUSTRIAL WATER SUPPLY',
     1/,10X,' D - DOWNSTREAM WATER SUPPLY')
      RETURN
      END
C
C
C
C*******************************************************************C
C                                                                   C
C                     SUBROUTINE CHANGE                             C
C                     =================                             C
C                                                                   C
C          THIS SUBROUTINE IS CALLED BY THE MAIN ROUTINE IF         C
C   THE PROBLEM NEEDS TO BE MODIFIED. MODIFICATIONS CAN BE          C
C   MADE WITH RESPECT TO THREE PARAMETERS:                          C
C                                                                   C
C          1. PRIORITY STRUCTURE                                    C
C          2. TARGET LEVEL OF EACH GOAL                             C
C          3. PROBABILITY LEVELS OF RECREATIONAL AND FLOOD          C
C             CONTROL GOALS.                                        C
C                                                                   C
C          THE FORMATS ARE DESIGNED FOR THE THREE-RESERVOIR         C
C   SYSTEM ANALYZED IN THIS RESEARCH. MODIFICATIONS NEED TO         C
C   BE MADE FOR OTHER SYSTEMS.                                      C
C                                                                   C
C*******************************************************************C
C
C
C
      SUBROUTINE CHANGE(NRES,PRIORITY)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION PRIORITY(15)
      COMMON /B10/ NVAR,NPRT,NUMDEV,RVLX(15,350),KPOS(150),MBAS(350)
      COMMON /B70/ SIGN(150),EQUALS(150)
      COMMON /B80/ CRV(3,2451),RPW(3,141),RHS(150),ORHS(150)
      COMMON /B90/ NDATA,ICODE,II,SINIT(10),HOUR(10),SLAST(10)
      COMMON /B100/ CAREA1(10),CAREA2(10),CERATE1(10),CERATE2(10)
      COMMON /B110/ CCAP1(10),CCAP2(10)
      COMMON /B120/ DIVIDE(10),TOP(10)
      COMMON /B130/ CSTORE(10),EVAP(10),PREV(10)
```

```
      COMMON /B140/ WATERM(10),WATERD(10),WATERP(10),WATERG(10)
      COMMON /B150/ XBAR21(10),STD21(10),PROB(150)
      COMMON /B160/ INDEXR(150),INDEXN(150),INDEXP(150),JOBJ
      COMMON /B170/ DIVIDE1(10)
      CHARACTER ANS*3,YES*3,NO*3
      CHARACTER*10 PRIORITY
      CHARACTER*4 GELC,CELC
      CHARACTER*4 FLCN,MIWS,DFWS,RECL,CONS
      CHARACTER*4 INDEXN,INDEXP
      DATA GELC/'GELC'/,CELC/'CELC'/
      DATA FLCN/'FLCN'/,MIWS/'MIWS'/,DFWS/'DFWS'/,RECL/'RECL'/
      DATA CONS/'CONS'/,RNOR/'RNOR'/
      DATA YES/'YES'/,NO/'NO'/
    5 WRITE(6,10)
   10 FORMAT(////,' THE USER"S PREFERENCE STRUCTURE CAN BE MODIFIED'
     1,' THROUGH:',//,'     (1). CHANGE THE RIGHT HAND SIDE VALUES'
     2,/,'     (2). CHANGE THE PROBABILITY LEVELS OF VARIOUS'
     3,/,'          CHANCE-CONSTRAINED GOALS',/,'     (3). CHANGE'
     4,' THE PRIORITY LEVELS OF VARIOUS GOALS',/,'     (4). EXIT'
     5,' SUBROUTINE CHANGE')
      WRITE(6,20)
   20 FORMAT(//,'  ENTER 1,2,3,OR 4:')
      READ(5,*) INUM
      GOTO(25,210,280,440) INUM
C
C     CHANGE RIGHT HAND SIDE VALUES.
C
   25 WRITE(6,30) NRES,(ORHS(I),I=1,NRES)
   30 FORMAT(//,' THE TARGETS FOR M&I WATER SUPPLY FOR THE',I2,
     1' RESERVOIRS(AC-FT) ARE',/,5X,F10.2,',',F10.2,', AND',F10.2)
      WRITE(6,40)
   40 FORMAT(//,' DO YOU WANT TO CHANGE ANY OF THESE VALUES?')
      WRITE(6,50)
   50 FORMAT(/,' ENTER "YES" OR "NO":')
      READ(5,51) ANS
   51 FORMAT(A3)
      IF(ANS.EQ.NO) GOTO 70
      WRITE(6,60) NRES
   60 FORMAT(//,' ENTER THE',I2,' NEW(OR PREVIOUS IF UNCHANGED) ',
     1'TARGET VALUES:')
      READ(5,*) (ORHS(I),I=1,NRES)
   70 WRITE(6,80) NRES,(ORHS(I),I=NRES+1,2*NRES)
   80 FORMAT(//,' THE TARGETS FOR DOWNSTREAM WATER SUPPLY FOR THE',
     1I2,' RESERVOIRS ARE',/,5X,F10.2,',',F10.2,',AND',F10.2)
      WRITE(6,40)
      WRITE(6,50)
      READ(5,51) ANS
      IF(ANS.EQ.NO) GOTO 90
      WRITE(6,60) NRES
      READ(5,*) (ORHS(I),I=NRES+1,2*NRES)
   90 WRITE(6,100) NRES,(ORHS(I),I=2*NRES+1,3*NRES)
  100 FORMAT(//,' THE TARGETS FOR POWER GENERATION FOR THE',I2,
```

```
     1' RESERVOIRS(KWH) ARE',/,5X,F15.2,',',F15.2,',AND',F15.2)
      WRITE(6,40)
      WRITE(6,50)
      READ(5,51) ANS
      IF(ANS.EQ.NO) GOTO 110
      WRITE(6,60) NRES
      READ(5,*) (ORHS(I),I=2*NRES+1,3*NRES)
  110 WRITE(6,120) NRES,(ORHS(I),I=3*NRES+1,4*NRES)
  120 FORMAT(//,' THE TARGET RELEASES FOR FLOOD PROTECTION  '
     1,/,' FOR THE',I2,' RESERVOIRS(AC-FT) ARE',/,5X,F10.2,',',
     2F10.2,', AND',F10.2)
      WRITE(6,40)
      WRITE(6,50)
      READ(5,51) ANS
      IF(ANS.EQ.NO) GOTO 130
      WRITE(6,60) NRES
      READ(5,*) (ORHS(I),I=3*NRES+1,4*NRES)
  130 WRITE(6,140) NRES,(ORHS(I),I=4*NRES+1,5*NRES)
  140 FORMAT(//,' THE TARGET RELEASES FOR RECREATION FOR THE',
     1I2,' RESERVOIRS(AC-FT) ARE',/,5X,F10.2,',',F10.2,',AND',
     2F10.2)
      WRITE(6,40)
      WRITE(6,50)
      READ(5,51) ANS
      IF(ANS.EQ.NO) GOTO 160
      WRITE(6,60) NRES
      READ(5,*) (ORHS(I),I=4*NRES+1,5*NRES)
  160 GOTO 5
C
C     CHANGE THE PROBABILITY LEVELS OF VARIOUS CHANCE-CONSTRAINED
C     GOALS.
C
  210 WRITE(6,220) NRES,(PROB(I),I=3*NRES+1,4*NRES)
  220 FORMAT(//,' THE PROBABILITY LEVELS FOR FLOOD PROTECTION '
     1,'FOR THE',I2,' RESERVOIRS ARE',/,5X,F5.2,',',F5.2,',AND'
     2,F5.2)
      WRITE(6,40)
      WRITE(6,50)
      READ(5,51) ANS
      IF(ANS.EQ.NO) GOTO 240
      WRITE(6,190) NRES
  190 FORMAT(//,' ENTER THE NEW(OR PREVIOUS IF UNCHANGED) OF THE',
     1I2,' PROBABILITY VALUES:')
      READ(5,*) (PROB(I),I=3*NRES+1,4*NRES)
  240 WRITE(6,250) NRES,(PROB(I),I=4*NRES+1,5*NRES)
  250 FORMAT(//,' THE PROBABILITY LEVELS FOR RECREATION FOR THE ',
     1I2,' RESERVOIRS ARE',/,5X,F5.2,',',F5.2,',AND',F5.2)
      WRITE(6,40)
      WRITE(6,50)
      READ(5,51) ANS
      IF(ANS.EQ.NO) GOTO 270
      WRITE(6,190) NRES
```

```
      READ(5,*) (PROB(I),I=4*NRES+1,5*NRES)
  270 GOTO 5
C
C     CHANGE THE PRIORITY LEVELS OF VARIOUS GOALS.
C
  280 WRITE(6,290)
  290 FORMAT(//,' FOR M&I WATER SUPPLY,')
      DO 295 I=1,JOBJ
      IF(INDEXP(I).EQ.MIWS) GOTO 296
  295 CONTINUE
  296 WRITE(6,300) RPW(2,I)-1,RPW(3,I)
  300 FORMAT(/,'     THE PRIORITY LEVEL IS',F3.0,/,'     THE WEIGHT'
     1,' WITHIN THE PRIORITY LEVEL IS',F3.0)
      WRITE(6,40)
      WRITE(6,50)
      READ(5,51) ANS
      IF(ANS.EQ.NO) GOTO 320
      WRITE(6,310)
  310 FORMAT(//,' ENTER THE NEW(OR PREVIOUS IF UNCHANGED) PRIORITY'
     1,' LEVEL AND ITS WEIGHT:')
      READ(5,*) NEWP,NEWW
      DO 315 K=I,I+NRES-1
      RPW(2,K)=NEWP+1
      RPW(3,K)=NEWW
  315 CONTINUE
  320 WRITE(6,330)
  330 FORMAT(//,' FOR DOWNSTREAM FLOW WATER SUPPLY,')
      DO 331 I=1,JOBJ
      IF(INDEXP(I).EQ.DFWS) GOTO 332
  331 CONTINUE
  332 WRITE(6,300) RPW(2,I)-1,RPW(3,I)
      WRITE(6,40)
      WRITE(6,50)
      READ(5,51) ANS
      IF(ANS.EQ.NO) GOTO 340
      WRITE(6,310)
      READ(5,*) NEWP,NEWW
      DO 335 K=I,I+NRES-1
      RPW(2,K)=NEWP+1
      RPW(3,K)=NEWW
  335 CONTINUE
  340 WRITE(6,350)
  350 FORMAT(//,' FOR POWER GENERATION PURPOSE,')
      DO 355 I=1,JOBJ
      IF(INDEXP(I).EQ.GELC) GOTO 356
  355 CONTINUE
  356 WRITE(6,300) RPW(2,I)-1,RPW(3,I)
      WRITE(6,40)
      WRITE(6,50)
      READ(5,51) ANS
      IF(ANS.EQ.NO) GOTO 370
      WRITE(6,310)
```

```
      READ(5,*) NEWP,NEWW
      DO 360 K=1,JOBJ
      IF(INDEXP(K).NE.GELC) GOTO 360
      RPW(2,K)=NEWP+1
      RPW(3,K)=NEWW
  360 CONTINUE
  370 WRITE(6,380)
  380 FORMAT(//,' FOR FLOOD PROTECTION PURPOSE,')
      DO 385 I=1,JOBJ
      IF(INDEXP(I).EQ.FLCN) GOTO 386
  385 CONTINUE
  386 WRITE(6,300) RPW(2,I)-1,RPW(3,I)
      WRITE(6,40)
      WRITE(6,50)
      READ(5,51) ANS
      IF(ANS.EQ.NO) GOTO 400
      WRITE(6,310)
      READ(5,*) NEWP,NEWW
      DO 390 K=I,I+NRES-1
      RPW(2,K)=NEWP+1
      RPW(3,K)=NEWW
  390 CONTINUE
  400 WRITE(6,410)
  410 FORMAT(//,' FOR RECREATIONAL PURPOSE,')
      DO 415 I=1,JOBJ
      IF(INDEXP(I).EQ.RECL) GOTO 416
  415 CONTINUE
  416 WRITE(6,300) RPW(2,I)-1,RPW(3,I)
      WRITE(6,40)
      WRITE(6,50)
      READ(5,51) ANS
      IF(ANS.EQ.NO) GOTO 424
      WRITE(6,310)
      READ(5,*) NEWP,NEWW
      DO 420 K=I,I+NRES-1
      RPW(2,K)=NEWP+1
      RPW(3,K)=NEWW
  420 CONTINUE
  424 WRITE(6,425)
  425 FORMAT(///,' ENTER THE NUMBER OF NEW PRIORITY LEVELS:')
      READ(5,*) INPRT
      NPRT=INPRT+1
      WRITE(6,426)
  426 FORMAT(//,' ENTER THE NAME OF EACH PRIORITY LEVEL:')
      DO 427 L=2,NPRT
      WRITE(6,428) L-1
  428 FORMAT(/,'     PRIORITY',I2,':')
      READ(5,429) PRIORITY(L)
  429 FORMAT(A10)
  427 CONTINUE
  430 GOTO 5
  440 INCREM=5*NRES
```

```
      DO 450 J=1,INCREM
      IF(PROB(J).LE.0.) GOTO 460
C
C     COMPUTE THE INVERSE CDF BY CALLING SUBROUTINE MDNRIS.
C
      CALL MDNRIS(PROB(J),YY)
      DINVS=XBAR21(INDEXR(J))+(STD21(INDEXR(J))*YY)
      IF(ICODE.EQ.2) DINVS=DEXP(DINVS)
      DINVS=59.505*DINVS
      CSTORE(INDEXR(J))=SLAST(INDEXR(J))
      RHS(J)=DINVS-ORHS(J)-EVAP(INDEXR(J))+CSTORE(INDEXR(J))
      IF(RHS(J).LT.0.00) RHS(J)=0.00
      GOTO 450
  460 IF(INDEXN(J).NE.GELC.AND.INDEXN(J).NE.CELC) GOTO 470
      CSTORE(INDEXR(J))=SLAST(INDEXR(J))
      IF(INDEXN(J).NE.GELC) GOTO 490
      DIVIDE(INDEXR(J))=CERATE1(INDEXR(J))+CERATE2(INDEXR(J))*
     1CSTORE(INDEXR(J))
      RHS(J)=ORHS(J)*1000.00/DIVIDE(INDEXR(J))
      GOTO 450
  490 TOP(INDEXR(J))=HOUR(INDEXR(J))*(CCAP1(INDEXR(J))+
     1CCAP2(INDEXR(J))*CSTORE(INDEXR(J)))
      DIVIDE1(INDEXR(J))=CERATE1(INDEXR(J))+CERATE2(INDEXR(J))*
     1CSTORE(INDEXR(J))
      RHS(J)=TOP(INDEXR(J))*1000.00/DIVIDE1(INDEXR(J))
      GOTO 450
  470 RHS(J)=ORHS(J)
  450 CONTINUE
      RETURN
      END
```

APPENDIX C

PERTINENT DATA OF DENISON, BROKEN BOW, AND PINE CREEK RESERVOIRS

Notes

The data in this appendix are used in the illustrated example provided in Chapter V. They are grouped into the following three categories:

1) Physical data, this includes Tables XIII-XX and Figures 14-20.

2) Hydrological data, Table XXI-XXIV

3) Demand data, Tables XXV-XXVIII

TABLE XIII

RESERVOIR MAXIMUM CAPACITY AND DEAD STORAGE (AC-FT)

	Reservoir (j)		
	Denison	Broken Bow	Pine Creek
Maximum capacity ($S_{j,max}$)	8512190	1604980	890250
Dead storage ($S_{j,min}$)	1031300	448250	7137

TABLE XIV

MAXIMUM ALLOWABLE RELEASE FOR M&I WATER SUPPLY (AC-FT)

	Reservoir (j)		
	Denison	Broken Bow	Pine Creek
Maximum allowable release ($W_{j,max}$)	3570300	476040	476040

TABLE XV

MAXIMUM ALLOWABLE AND MINIMUM REQUIRED RELEASES FOR DOWNSTREAM WATER SUPPLY (AC-FT)

	Reservoir (j)		
	Denison	Broken Bow	Pine Creek
Maximum allowable release ($G_{j,max}$)	3570300	476040	470040
Minimum required release ($G_{j,min}$)	4463	5951	3868

TABLE XVI

RELATIONSHIPS BETWEEN STORAGE AND AREA; ENERGY RATE; POWER PLANT CAPACITY; AND ELEVATION OF DENISON RESERVOIR

Storage (Ac-Ft)	Area (Acres)	Energy Rate (KWHr/KAC-Ft)	Power Plant Capacity (KW)	Elevation (NGVD)
1119100	44740	68667	57000	592
1210300	46380	70340	60000	594
1304700	48020	72161	62500	596
1402300	49660	73975	65000	598
1503300	51300	75653	66800	600
1626000	55394	77963	70000	602
1727700	58420	78873	72000	604
1843100	61980	80955	74500	606
1970700	65540	82672	77000	608
2105300	69600	84814	79000	610
2168700	77130	85899	80500	614
2398800	79015	87466	80500	615
2733300	91000	89897	80500	618
2920300	96000	93671	80500	620
3116900	100640	95061	80500	622
3322900	105280	96762	80500	624
3538100	109920	98559	80500	626
3762500	114560	100357	80500	628
3996300	119200	102062	80500	630
4239700	124160	103825	80500	632
4492900	129120	105632	80500	634
4756100	134080	107359	80500	636
5029300	139040	109089	80500	638
5312300	144000	110894	80500	640
5605600	149320	112649	80500	642
5909600	154640	114385	80500	644
6224200	159960	116161	80500	646
6549400	165280	117934	80500	648
6885300	170600	119672	80500	650
7232000	176140	121454	80500	652
7589900	181680	123172	80500	654
7958800	187220	124960	80500	656

TABLE XVII

RELATIONSHIPS BETWEEN STORAGE AND AREA; ENERGY RATE; POWER PLANT CAPACITY; AND ELEVATION OF BROKEN BOW RESERVOIR

Storage (Ac-Ft)	Area (Acres)	Energy Rate (KWHr/KAC-Ft)	Power Plant Capacity (KW)	Elevation (NGVD)
457480	9280	126436	76200	560
476270	9510	131134	78200	562
495530	9750	132866	80250	564
515250	9980	134686	82300	566
535390	10180	136544	84400	568
555990	10430	138252	86500	570
577090	10680	139953	88600	572
598680	10920	141779	90740	574
620760	11150	143342	92800	576
643330	11400	145104	94800	578
666380	11650	146941	96900	580
689950	11900	149212	99000	582
714040	12180	149814	101000	584
738650	12400	152052	103100	586
763740	12670	153886	105200	588
789330	12920	155764	107300	590
815440	13190	157526	109400	592
842070	13460	159369	111400	594
869250	13720	161038	113500	596
869950	13980	162816	115000	598
925180	14250	165120	115000	600
953980	14550	166319	115000	602
983370	14820	167982	115000	604
1013320	15120	169783	115000	606
1043830	15380	171518	115000	608
1074860	15650	173380	115000	610
1106390	15880	175103	115000	612
1138410	16120	176765	115000	614
1170950	16400	178549	115000	616
1204010	16650	180339	115000	618
1237590	16920	182102	115000	620
1271690	17180	184471	115000	622
1306320	17450	185677	115000	624
1341490	17720	187342	115000	626
1377210	18000	189194	115000	628
1413510	18370	191350	115000	630
1450410	18750	193848	115000	632

TABLE XVIII

RELATIONSHIPS BETWEEN STORAGE AND AREA; AND ELEVATION OF PINE CREEK RESERVOIR

Storage (AC-Ft)	Area (Acres)	Elevation (NGVD)
7137	700	414
8675	840	416
10510	1000	418
12680	1170	420
15210	1360	422
18130	1570	424
21500	1800	426
25350	2050	428
29730	2330	430
34700	2640	432
40320	2980	434
46650	3350	436
53750	3750	438
61680	4180	440
70490	4630	442
80220	5100	444
90920	5600	446
102650	6130	448
115450	6680	450
129380	7250	452
144480	7850	454
160790	8470	456
178370	9110	458
197250	9770	460
217470	10450	462
239080	11160	464
262140	11900	466
286690	12650	468
312730	13400	470
340280	14160	472
369350	14920	474
399950	15690	476
432090	16460	478
465780	17230	480
501020	18010	482

TABLE XIX

SUMMARY OF REGRESSION ANALYSIS RESULTS

	Reservoir					
	Denison		Broken Bow		Pine Creek	
	Intercept	Slope	Intercept	Slope	Intercept	Slope
Energy rate (ξ) vs. Storage (S)	66694.0497	0.0080	103451.3762	0.0641	-	-
Power Plant Capacity (PMAX) vs. Storage (S)	32859.7038 80500	0.0224[1] -	36671.8054 115000	0.0890[2] -	-	-
Area (AREA) vs. Storage (S)	25602.6457	0.0217	5287.060	0.0095	1929.1776	0.0352

[1] S $\leq$2105300 Ac-Ft
[2] S $\leq$ 92518 Ac-Ft

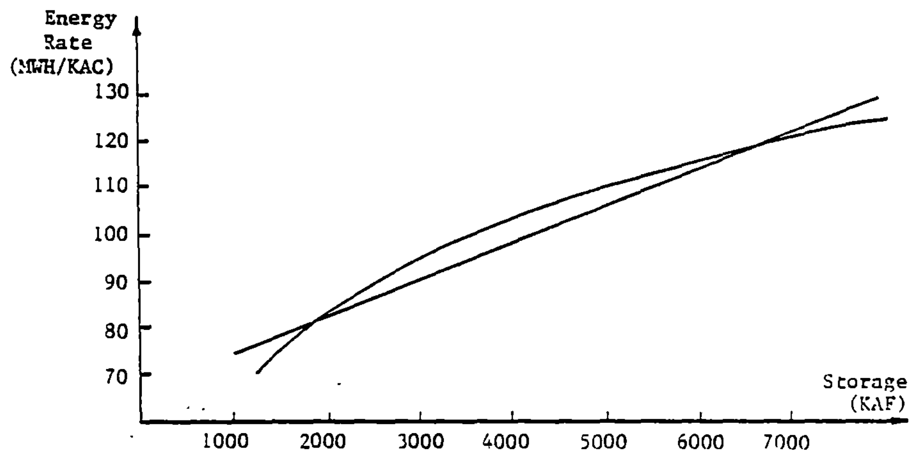

Figure 14. Plots of Energy Rate Against Storage for Denison Reservoir

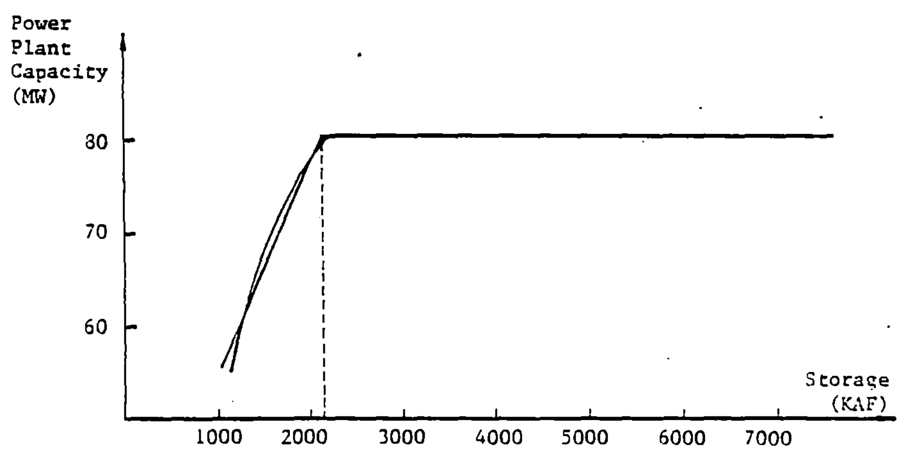

Figure 15. Plots of Power Plant Capacity Against Storage for Denison Reservoir

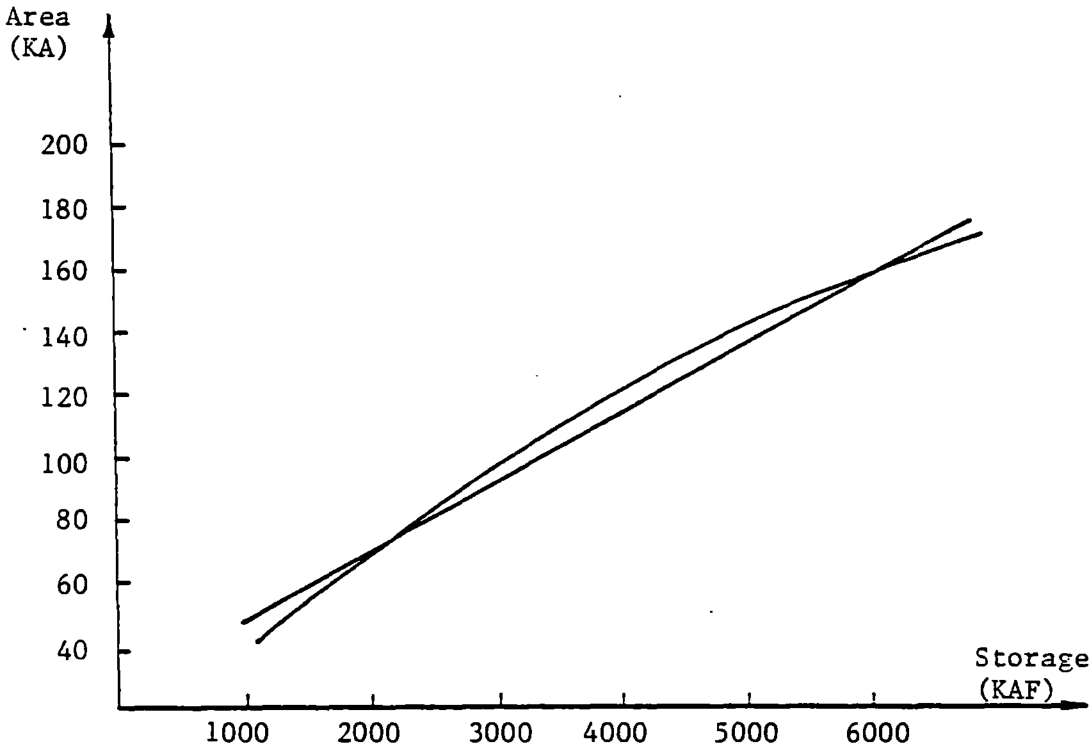

Figure 16. Plots of Surface Area Against Storage for Denison Reservoir

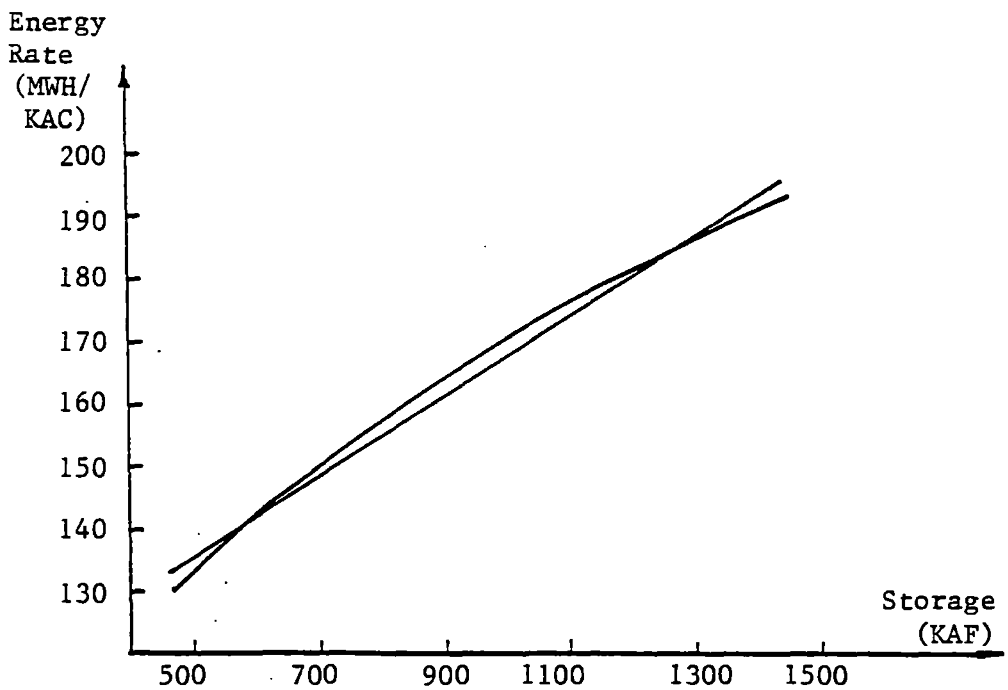

Figure 17. Plots of Energy Rate Against Storage for Broken Bow Reservoir

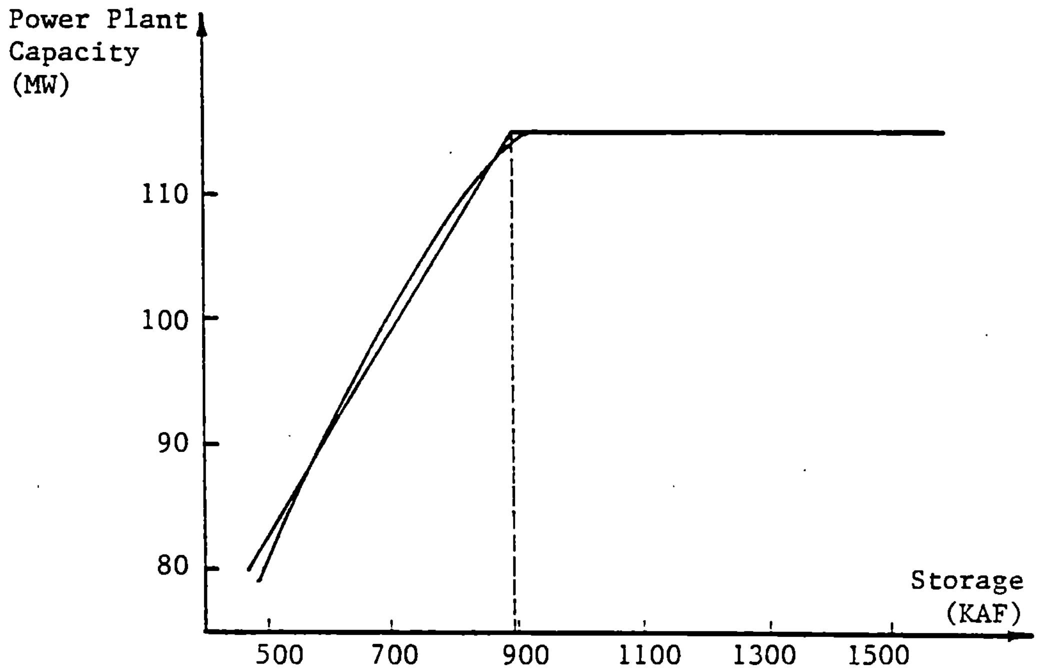

Figure 18. Plots of Power Plant Capacity Against Storage for Broken Bow Reservoir

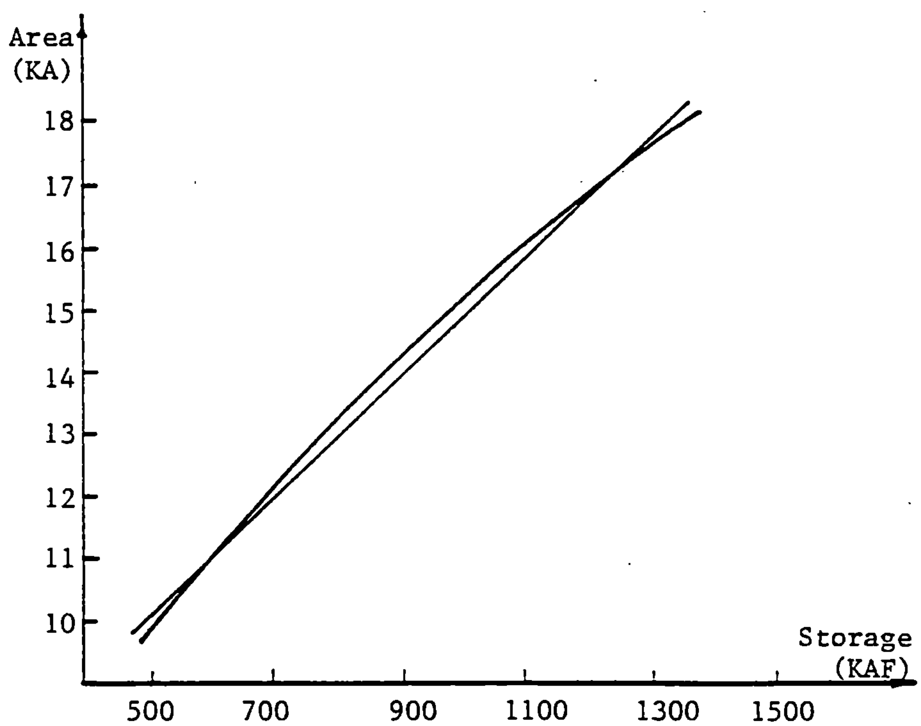

Figure 19. Plots of Surface Area Against Storage for Broken Bow Reservoir

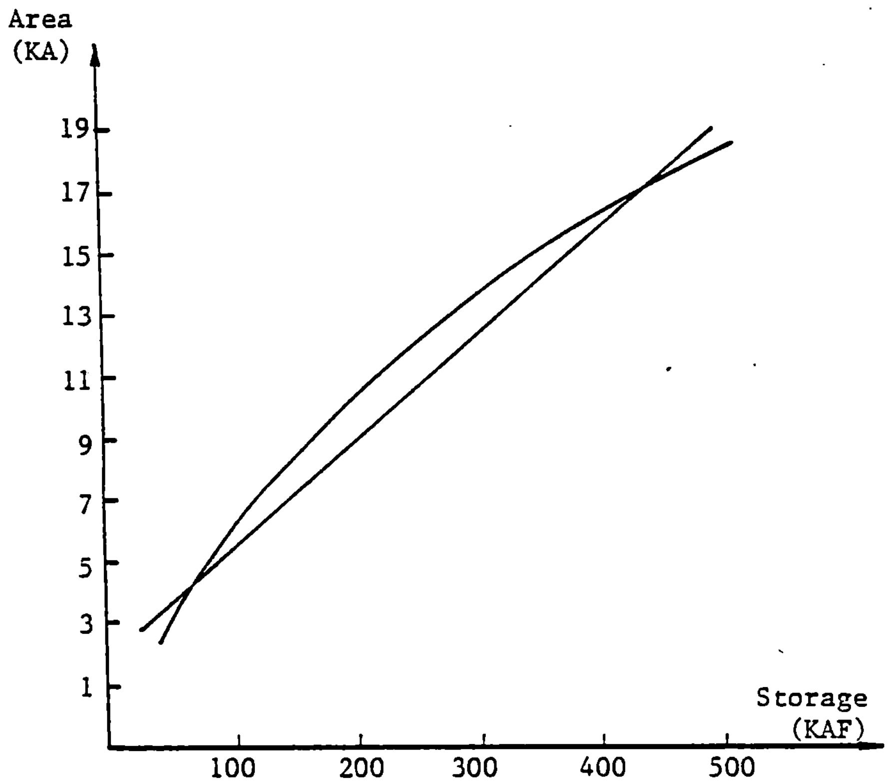

Figure 20. Plots of Surface Area Against Storage for Pine Creek Reservoir

TABLE XX

TOTAL NUMBER OF HOURS IN EACH MONTH

Month	Total Hours
January	744
February	672
March	744
April	720
May	744
June	720
July	744
August	744
September	720
October	744
November	720
December	744

TABLE XXI

MONTHLY HISTORICAL INFLOW FOR DENISON RESERVOIR (CFS)[1]

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
1923	610	3911	1403	4223	15040	22116	1721	680	8100	34868	14772	9872
1924	2830	1719	4960	9596	6229	2672	1675	1342	1111	1098	738	681
1925	742	745	581	5092	7676	1225	574	3984	16805	6164	2840	759
1926	1581	1019	1935	5999	5904	3395	7367	9026	5025	26672	2538	5107
1927	4489	4735	4586	26317	4066	5781	8571	4293	1781	6196	1301	2781
1928	2046	2769	1464	5947	14958	18584	7489	2648	613	476	1000	1202
1929	1478	1098	2987	4429	17252	9398	3214	368	8395	1931	2191	1558
1930	1532	5028	2007	827	21171	8291	1008	275	642	8935	1576	7982
1931	1326	5484	4185	3287	4243	1069	2998	553	98	4487	4619	4565
1932	13418	12031	2790	2694	5568	13735	12325	2196	3258	1146	486	4884
1933	2714	1058	5428	3068	21490	2483	1369	4386	5212	1450	922	1055
1934	1723	1672	4824	1248	3050	1684	244	199	4730	1133	3106	1006
1935	685	493	5938	2884	42210	21813	5635	1975	5423	1341	1439	4936
1936	1028	810	877	375	7628	6115	948	142	15006	7118	1053	1294
1937	2394	1304	2773	3887	782	10415	1113	3702	2621	3575	834	1452
1938	2474	19628	10074	7229	17251	10729	2156	1167	678	332	497	280
1939	1461	706	837	2167	997	2886	1955	1622	257	311	316	171
1940	90	411	137	3088	7211	6861	6752	3373	1127	214	4126	3258
1941	2142	7029	2092	8629	29139	50796	7022	2924	4652	40533	25144	5043
1942	2734	2691	2907	43108	13977	10274	2317	2107	5603	7073	7931	2769
1943	2769	1629	2306	9248	26723	11395	1783	370	412	498	336	286
1944	1061	4139	4292	2903	5134	6222	1232	898	357	3548	1810	2231
1945	1757	7676	31056	22140	5902	17042	12113	4235	7051	19676	1491	916
1946	7797	9595	4629	3547	5776	8133	3769	1891	2701	2075	5466	12680
1947	1562	871	1447	13939	34458	12666	2284	715	104	792	954	4682
1948	999	4651	6088	1521	7641	7649	7213	735	220	200	200	125
1949	1341	7134	3516	2094	15971	14041	1460	483	3794	3277	563	1005
1950	2940	4435	730	1576	22826	6516	14768	17091	13931	3445	469	703
1951	1115	2436	2333	1176	25297	29664	6368	804	812	1016	1063	200
1952	528	811	1600	5278	8969	2965	105	90	80	70	95	338
1953	260	292	2229	3739	2706	1480	4110	1895	486	9905	4440	1915
1954	989	254	300	1994	26457	6227	100	100	100	1129	35	794
1955	751	1136	1763	1615	18871	11857	2700	1370	5335	16624	1308	676
1956	571	1541	782	722	4160	2973	1095	383	17	1072	1046	1091
1957	452	1279	2177	28499	75634	32171	3487	1428	6309	2266	9990	1785
1958	4615	2227	4136	5586	13191	4253	3528	1713	547	219	365	346
1959	501	554	1042	2740	6526	8112	5872	2251	2857	16662	2556	7099
1960	6484	7159	4318	2935	6485	6299	4340	1452	1344	12306	2282	5136
1961	2124	2914	5702	5499	4066	7995	4317	1437	4333	3181	5588	3209
1962	1230	1755	1809	3235	2953	25106	3588	2187	6776	2886	5513	4428
1963	1044	1572	2372	4105	2284	4121	1288	171	451	155	252	330
1964	408	1345	1390	2028	3363	3235	474	1464	4443	1094	8654	1559
1965	1446	2443	1053	2205	5810	5692	1603	697	5608	6883	1644	1018
1966	1116	3928	1814	8718	4642	1207	466	3128	5896	1947	215	250
1967	492	501	695	11851	4325	5091	2982	784	2355	848	590	725

[1] 1 CFS (Cubic Feet Per Second) = 1.9835 Ac-Ft/Day

TABLE XXII

MONTHLY HISTORICAL INFLOW FOR BROKEN BOW RESERVOIR (CFS)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
1923	626	890	3837	1973	4635	0	59	468	1650	408	632	5755
1924	755	2862	1406	1887	849	317	29	4	16	10	23	183
1925	531	696	243	891	287	1705	139	102	28	1408	1245	402
1926	2189	1580	1859	2152	878	493	26	31	27	1066	659	7358
1927	4774	1286	3202	5298	1670	0	318	748	36	640	412	999
1928	1644	1015	880	5776	492	0	860	2479	15	0	398	4938
1929	2075	1795	1844	1015	2659	12	175	19	406	296	853	1705
1930	2522	1633	957	227	6092	115	6	1	10	207	758	1168
1931	75	2638	1839	482	645	132	1000	165	33	240	625	2210
1932	7691	5149	932	936	415	644	2313	45	10	19	87	2698
1933	2708	1565	2404	1692	1673	106	71	205	855	457	390	990
1934	994	311	1839	2106	277	24	1	1	269	202	1563	955
1935	3614	700	3932	2775	6403	4511	148	23	62	500	1486	1952
1936	245	537	891	161	763	42	157	2	277	903	725	1942
1937	4825	816	1499	1968	1546	667	46	629	1041	581	1327	1622
1938	5957	5870	2396	2969	919	692	74	40	7	1	21	172
1939	605	3473	2282	4929	970	278	77	94	4	30	80	313
1940	323	823	415	2363	3726	886	1690	1033	92	21	1373	1786
1941	1250	1876	856	2506	789	1434	186	40	64	1588	1832	1530
1942	1028	1203	2054	3322	1447	404	89	179	198	22	1090	1638
1943	416	304	1222	1655	671	359	23	1	2	18	291	955
1944	915	6467	3225	2069	4198	755	48	21	45	2	406	1896
1945	853	3756	10239	1850	3014	3410	257	583	2237	1704	446	438
1946	3788	4150	1968	2175	5351	1065	74	19	3	7	3257	3100
1947	655	262	1252	2200	3576	164	31	2023	501	337	1269	3007
1948	2677	4532	2278	947	2150	87	93	106	13	5	92	579
1949	6135	2697	2386	1178	2426	2344	523	90	83	780	192	1789
1950	6562	6473	1216	936	4256	307	2086	1751	3132	269	155	82
1951	564	4075	1228	1096	670	2122	2366	93	169	342	2079	1471
1952	1605	1192	1910	7034	750	111	13	2	3	18	1100	1239
1953	1304	1717	3266	5160	4005	74	2360	130	18	2	17	328
1954	2329	1598	298	1176	2290	75	5	5	108	2682	448	899
1955	964	2024	2392	1766	1044	193	81	89	268	446	38	81
1956	267	3547	793	476	1063	52	8	3	4	4	257	686
1957	1937	1984	2769	7876	4726	2236	83	42	558	163	1892	907
1958	1529	583	3359	2474	3488	893	221	224	260	338	2538	420
1959	487	1110	2053	1301	667	285	850	155	165	1366	482	3296
1960	2296	1559	1312	682	4869	689	1455	595	82	93	178	3749
1961	984	1638	2874	1473	2523	287	848	377	305	423	2151	2382
1962	2696	1783	1662	1715	393	232	21	46	183	1743	703	470
1963	637	184	2124	918	399	36	66	43	19	3	4	7
1964	15	329	2455	2872	460	46	2	504	801	319	1234	594
1965	1208	3604	1217	779	2586	1787	140	13	396	187	101	192
1966	521	2890	482	2520	1690	44	7	575	230	17	18	104
1967	172	230	902	2580	2630	783	772	26	239	845	849	2919

TABLE XXIII

MONTHLY HISTORICAL INFLOW FOR PINE CREEK RESERVOIR (CFS)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
1923	403	1410	2530	886	2935	1264	8	51	1820	411	696	2799
1924	813	1455	618	1049	296	120	8	8	0	0	71	121
1925	521	664	298	830	239	22	402	25	690	1164	977	379
1926	1417	404	837	789	1358	92	87	17	170	487	564	6049
1927	2853	1079	1804	4175	960	55	316	563	74	240	144	644
1928	639	626	313	4189	701	1640	139	1504	26	0	270	2951
1929	2053	1317	1001	536	2568	302	116	14	3355	267	498	2470
1930	1238	1082	811	210	4259	96	20	4	5	146	238	705
1931	42	1933	1298	356	519	54	10	35	3	259	464	1171
1932	1171	2749	560	490	565	1237	911	18	3	4	10	1225
1933	1425	928	1682	1561	1267	47	24	362	331	256	127	504
1934	957	224	223	2165	203	9	1	1	255	36	1017	376
1935	2044	727	326	2123	5650	4618	122	22	14	120	830	1628
1936	216	443	466	80	752	32	36	2	230	776	453	1189
1937	16754	4602	2621	1919	4150	4867	413	51	624	1337	1379	3816
1938	2551	4380	1712	2476	804	670	23	19	14	2	21	114
1939	303	2476	1224	2978	376	255	68	19	3	2	6	65
1940	95	241	135	1356	2817	370	1053	419	198	34	1293	1884
1941	937	1309	567	2917	584	1415	102	42	18	355	806	840
1942	434	697	856	3058	1624	545	59	37	154	18	889	1179
1943	272	286	731	1276	1216	302	30	3	2	17	168	494
1944	815	3166	1726	1603	2775	472	26	9	36	1	689	1259
1945	610	4004	6928	1331	2631	4078	802	332	932	736	245	170
1946	1936	3020	965	2286	3055	644	30	3	3	7	3556	2986
1947	456	137	1099	2228	2652	101	12	1	2	3	147	1355
1948	1303	1909	1468	623	2173	81	40	9	1	9	5	90
1949	5266	2219	1611	1015	2486	852	241	47	245	827	166	814
1950	4020	4333	445	600	2803	118	2247	1660	3429	157	93	57
1951	532	3393	683	981	617	3421	1592	30	24	228	1245	642
1952	482	554	1578	4258	573	168	24	8	4	1	115	298
1953	332	673	2074	3967	2473	43	2148	96	24	3	6	227
1954	1807	424	102	669	2221	193	4	1	84	2083	306	751
1955	745	1187	1632	691	414	64	3	51	970	438	22	40
1956	42	2016	478	269	943	104	4	1	1	1	166	336
1957	1004	1777	1875	5340	4052	1468	37	31	1567	101	2593	748
1958	1333	639	2049	1444	2814	112	242	83	283	90	458	225
1959	272	442	1018	696	385	135	1125	145	60	437	470	1753
1960	1551	911	827	332	3448	200	859	273	38	96	45	1686
1961	669	1190	1100	796	2540	194	607	335	314	380	1610	1538
1962	1274	1048	923	1929	243	240	15	3	340	1289	689	573
1963	574	129	1042	708	255	13	105	24	11	1	1	5
1964	3	130	1077	2017	579	59	7	321	685	161	851	540
1965	685	2060	902	726	1135	275	33	59	632	51	120	92
1966	336	1451	346	2014	1070	26	12	317	102	7	4	47
1967	77	96	302	1709	1655	535	111	3	630	270	521	1427

TABLE XXIV

AVERAGE MONTHLY EVAPORATION FROM THE RESERVOIR (FT)

Month	Reservoir		
	Denison	Broken Bow	Pine Creek
January	1.14	-1.68	-1.29
February	1.46	-1.27	-0.91
March	3.23	0.00	-0.07
April	3.71	0.11	0.09
May	4.18	0.17	0.18
June	5.78	2.65	3.13
July	6.47	3.27	3.40
August	6.47	3.12	4.42
September	4.46	1.48	2.65
October	2.73	0.28	1.31
November	1.96	-0.65	-0.47
December	1.04	-1.22	-0.92

TABLE XXV

MONTHLY DEMANDS FOR M&I AND DOWNSTREAM
WATER SUPPLY (AC-FT)

	Reservoir (j)		
	Denison	Broken Bow	Pine Creek
Demand for M&I water supply ($W_{j,t}$)	2762	5985	7734
Demand for downstream water supply ($D_{j,t}$)	None	10128	3314

TABLE XXVI

MONTHLY DEMAND FOR HYDROELECTRIC POWER GENERATION (MWH)

Month	Reservoir	
	Denison	Broken Bow
January	10040	5050
February	8020	4480
March	9010	4540
April	8970	4670
May	11200	5640
June	12580	6560
July	14030	7070
August	13780	6950
September	10960	5720
October	9520	4800
November	8840	4610
December	9520	4800

TABLE XXVII

MONTHLY FLOOD PROTECTION STORAGE (AC-FT)

Month	Reservoir		
	Denison	Broken Bow	Pine Creek
January	2665000	918070	53750
February	2665000	918070	53750
March	2665000	918070	61680
April	2665000	918070	70490
May	2665000	918070	70490
June	2665000	918070	70490
July	2665000	918070	70490
August	2665000	918070	61680
September	2665000	918070	61680
October	2665000	918070	53750
November	2665000	918070	53750
December	2665000	918070	53750

TABLE XXVIII

DESIRABLE RECREATIONAL STORAGE (AC-FT)

	Reservoir (j)		
	Denison	Broken Bow	Pine Creek
Maximum desirable storage ($RCMAX_{j,t}$)	2556800	918070	53750
Minimum desirable storage ($RCMIN_{j,t}$)	225000	815440	34700

2

VITA

Chawengsak Changchit

Candidate for the Degree of

Doctor of Philosophy

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