RESERVOIR OPERATION
FOR WATER CONSERVATION

by

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for

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RESERVOIR OPERATION FOR WATER CONSERVATION

EXECUTIVE SUMMARY

Background

The demand for a continual supply of fresh water, whether it be for agricultural, municipal or industrial use, is presently only a small fraction of the total supply of fresh water on the earth. However, economic and technological factors limit the available supply of fresh water to such an extent that competition for its use has been increasing rapidly over the years. The resulting concern over possible future water shortages has created a need for studying ways by which more efficient management of water can be accomplished by the prevention of avoidable water losses.

Surface water storage reservoirs have become an important element in water supply systems. Their fundamental function is the retention of streamflow during periods of high flow. An unfortunate consequence of the storage of surface water is the increase in infiltration losses and, more significantly, evaporation losses. Often the construction of a reservoir results in evaporation losses many times in excess of the natural evaporation and transpiration losses.

The quantity of water lost to the atmosphere by evaporation varies in relation to climatic conditions and geographic location; thus the magnitude and significance of evaporation losses from reservoirs varies accordingly. In the U.S., mean annual lake evaporation varies from about 20 inches in the Northeast to about 86 inches in the Southwest. Evaporation studies at Lake Hefner, Oklahoma indicate that the evaporation loss averaged about 90% of the outflow of the reservoir. Investigations at Lake Mead, Nevada show that over 800,000 acre-feet of water per year is lost to the atmosphere by evaporation from the lake surface. In Illinois, it has been reported that, during a severe drought, communities attempted to alleviate possible future shortages by curtailing water use only to find that the subsequent loss to evaporation from their reservoirs was two or three times the water normally used by the communities.

Objective

The objective of this study is to assess the potential for conservation of water through modifications in the design or operation of existing and proposed reservoirs. Recognizing that the management of water and the manner in which water is used vary with hydrologic, climatological and physical conditions, a variety of these factors is studied.

General Approach

It is recognized that the design and operation of reservoirs are constrained in so many ways that there is often little opportunity to modify either the design or operation without impinging on legal rights or vested interests. Nevertheless, the many wasteful conditions that result from these constraints must be overcome if the water resources of a region are to be utilized to their fullest, as appears to be a necessity in some regions. Accordingly, this study examines the capability of conserving water on the premise that these constraints can eventually be removed in a manner satisfactory to all. The results of the study can then be used to determine the gain that is possible under altenative plans of management. Two approaches were used to study conservation potential through reservoir design and operation. In the first approach, hypothetical reservoir systems in arid, semi-arid and humid regions were used in conjunction with a computer model developed specifically for this research, tailored to fit the needs of an evaporation reduction study. The model so developed (RESEVAP) utilizes a DP algorithm applied to a two-reservoir system incorporating a single state variable. The model is capable of simulating the two-reservoir system in parallel or in series, and can optimize over any of three possible objective functions: minimize cumulative evaporation, minimize cumulative spill, or minimize the cumulative sum of evaporation and spill. The various methods of evaporation calculation were considered and the most practical method, utilizing pan evaporation data, was employed in the computer model.

In the second approach, existing systems and actual data were used to test and evaluate conservation measures. Results were essentially the same in each approach, and the second approach will be described in the remainder of this executive summary.

Project Examples

It is considered that practical results can best be obtained through the use of actual project data. Accordingly, three projects were selected for the purpose of obtaining reservoir physical data, streamflow data and a variety of demand patterns in humid, semi-arid and arid regions. While three projects cannot encompass all the conditions and combinations of conditions that exist, it is considered that these projects and variations introduced reasonably represent most of the situations encountered.

The optimal yield or maximum conservation under each alternative management plan is obtained through successive approximations in detailed simulation of the reservoir operation for the period of recorded streamflows, using computer program HEC-3, "Reservoir System Operation for Conservation."

Three project examples have been selected to represent a broad spectrum of conditions and problems in reservoir management.

A system of four reservoirs in the fairly arid region of west Texas was selected for one example. Reservoir configuration, characteristics and inflows were obtained for the four reservoirs of the upper Colorado River basin of Texas. While these reservoirs represent only a small part of the water resource system of that basin, they are used as though they constitute a complete system for using water as necessary for local needs. Thus, it is not intended to conform to the legal and institutional constraints that exist, but rather, for the purpose of this study, to examine the operation from the standpoint of the most effective conservation practice from a simplified hypothetical standpoint.

In connection with these four reservoirs, a groundwater operation is hypothesized in order to assess the potential impacts of conjunctive use of groundwater and surface water. This system was studied to determine:

a. Conservation potential through different distributions of stored water among the four reservoirs.
b. Conservation potential through different plans of conjunctive use of groundwater.

The second project selected is Pine Flat Reservoir in a semi-arid region of California. This reservoir is located in a narrow canyon and is operated primarily for flood control and irrigation, where water rights greatly exceed normal annual streamflows. Even in very wet years, most of the water is usable. Of course, the entities holding junior rights cannot economically develop their farming operations to a high degree, since years of no water would be a heavy financial drain under a high-capital-investment type of operation. Much of the water in wet years is used in irrigated pasture and similar low-income endeavors. The operation of Pine Flat was studied to determine:

a. Conservation potential through different mixes of firm supply for high-capital-investment uses and secondary supply for low-investment uses.
b. Conservation potential through increasing the size of the reservoir and thus reducing the amount of wasted water in wet years.
c. Conservation effected because of the location of the reservoir in a narrow valley as contrasted with location in a broad valley exposing larger areas to evaporation losses (a design consideration).
d. Conservation through increasing the yield by simply accepting damaging shortages during severe droughts.

The third project is Sam Rayburn Reservoir in the humid east Texas, which is an expansive lake with large storage capacity and large inflow. There is a power plant at the dam. The operation of this reservoir was studied to determine:

a. Increased yield obtainable by a two-level water demand (with primary supply highly dependable and secondary supply curtailed during droughts) as contrasted to a one-level firm supply.
b. The effects of this on evaporation losses and power generation.

Discussion of Results

Studies described herein were designed to apply to complete reservoir systems. Although case studies were derived from partial systems for the sake of simplicity and manageability, they represent complete systems. Results of studying incomplete systems as such would be inconclusive.

It is apparent that conservation of water (maximizing its availability for the most effective use) can best be accomplished in a closed system through storage. During initial stages of development, great gains in conservation can be accomplished ordinarily through provision of surface storage. Surface storage is most effective where time variations in flow are large. This is characteristic of semi-arid and arid regions, where evaporation rates are also high. Generally, losses in evaporation are small compared to losses through spill due to inadequacy of storage.

During the later stages of river development where substantial storage exists, provision of additional storage is decreasingly effective, because the critical drought period becomes longer, which subjects the stored water to longer periods of evaporation before it is released or used. As this stage approaches, integration of the operation of surface storage with aquifer storage can substantially improve the effectiveness of the increased storage. In essence, long-term storage should be in an aquifer where losses are small or negligible, and short-term storage should be in surface reservoirs. This is illustrated in the first project examples (Tables 14 and 15 of the main report). By adding three upstream reservoirs in this hypothetical system, the yield is decreased from 100 to 85 cfs in addition to a zero or constant groundwater withdrawal. However, if a well field capacity is expanded from 19 to 60 cfs and used only when droughts are well under way, the yield of surface runoff rises from 84 to 97 cfs. Thus, the yield is raised 13 cfs simply by allowing water to stay underground during periods of adequate surface runoff.

Another way of conserving water during later stages of river development is to distribute water, insofar as is feasible, among reservoirs so that storage is concentrated in those reservoirs that have the least increase in area per unit of storage increase, giving consideration also to any differences in net evaporation rates that might exist at the different reservoirs. From a practical or political (social) standpoint, this may be very difficult because of the multiple uses of reservoir facilities. It is interesting to note in Tables 14 and 15 that, using this technique, the four-reservoir yield from surface runoff rises from 85 cfs when storage is proportionately distributed among the four reservoirs to 96 cfs when it is kept in the downstream reservoir to the maximum extent possible. If the upstream reservoirs did not exist, the yield would increase to 100 cfs.

Another feature of the later stages of river development, illustrated in Tables 14 and 15, is the high evaporation losses compared to yield. In this case, evaporation ranges from 55 to 66 cfs for yields averaging about 90 cfs. Thus, about 40 percent of the available water is sacrificed in order to obtain a maximum dependable water supply in this case.

A very general appraisal of water conservation factors in relation to the degree of water resource development can be made by reviewing Tables 14, 21 and 25 of the main report. The case of Pine Flat reservoir is that of least storage development in relation to potential development. The average runoff used is 2118 cfs, and the maximum dependable yield for the existing reservoir (1,001,000 acre-feet) is 1132 cfs. Evaporation losses are trivial in relation to the spill of 957 cfs. With a 6,000,000 acre-foot reservoir, the yield could become 1934 cfs while the losses remain nominal at 66 cfs. Sam Rayburn Reservoir, on the other hand, represents a moderately high degree of development. A yield of 2444 cfs is obtainable, compared to an average inflow of 3245. Because of the humid climate, evaporation losses are a low 78 cfs. Spill is very substantial at 669 cfs, indicating that further conservation can be obtained through provision of more storage. The four-reservoir Colorado River system represents full development. A yield of 85 cfs is obtained from an average runoff of 151 cfs. The difference is lost through evaporation, which is largely due to the arid climate and the necessity to use broad valleys for relatively shallow reservoirs. Further conservation potential through reservoir construction and management is relatively small.

While variable demand patterns depending on water availability have been studied, they are generally of interest only during intermediate stages of development. In municipal and industrial uses, as well as in hydropower generation, water is of high value and is effectively useful only insofar as its supply is dependable. Even in agriculture, the dependability factor is becoming more important as large investments in farmland development and high-yield crops can be hurt seriously by water shortages. More and more is supplementary water of little value and shortage a great cost. The response function for water-related investments then has a sharp break at the point of dependable yield. It is this condition that must be considered in assessing conservation accomplishments. If the firm yield of a system is increased, water is conserved. If it is decreased, water is wasted. Of course, this applies to a complete system including water needs in estuaries.

Conclusions

1. Conservation of water must be associated with greater utilization and not simply reduced losses of any type or types.
2. In the early stages of regional water development, surface storage is a highly effective means of conserving water for effective use.
3. As regional water resources become highly developed, underground storage in aquifers, using natural replenishment and controlled withdrawal, can substantially reduce losses and increase the utility of water resources.
4. In dry regions, losses to evaporation from long-term carry-over by surface reservoirs can be a high percentage of the usable firm yield.
5. In humid regions, evaporation losses are generally of minor or even trivial significance.
6. Where a low degree of reservoir regulation exists, a 2-stage demand can be very useful, where only priority uses are served during low reservoir stages. With a high degree of regulation and generally in humid regions, little, if any, gain is made by supplying supplementary water at high reservoir stages at the expense of reducing the firm yield at lower stages.
7. Substantial water savings can be effected, especially in dry regions, by distributing the water among reservoirs in a system so as to reduce over-all evaporation losses, where feasible.
8. In dry regions, losses can be greatly reduced by using deep reservoirs instead of shallow reservoirs.
9. With a fixed amount of storage, water yield and utilization can be greatly increased simply by delivering water at a higher rate until the supply is exhaused. For some uses, such as irrigation, this can produce more benefits than losses over the long term.
10. For a given reservoir, as the yield or usage of water increases, power generation is first increased because of reduction in spill, and then decreased because of maintenance of lower reservoir contents and consequently lower heads.

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CHAPTER I
INTRODUCTION

Background

The demand for a continual supply of fresh water, whether it be for agricultural, municipal or industrial use, is presently only a small fraction of the total supply of fresh water on the earth. However, economic and technological factors limit the available supply of fresh water to such an extent that competition for its use has been increasing rapidly over the years. The resulting concern over possible future water shortages has created a need for studying ways by which more efficient management of water can be accomplished by the prevention of avoidable water losses.

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Reservoir System Operation

The term reservoir system refers to a set of two or more reservoirs lying within the same river basin and operating to serve a common purpose or purposes. The more important purposes include flood control, water conservation, hydroelectric power generation and maintenance of adequate water levels for recreation. Ideally, each reservoir in the system is operated with respect to conditions at the other reservoirs, and the sytem as a whole is operated to fulfill its intended purposes.

The operation of a reservoir system for the purpose of flood control requires that adequate storage be reserved for the impoundment of flood waters. Operation for the purpose of water conservation attempts to maximize the yield from the reservoir system. Both hydroelectric power generation and recreational purposes are best served when the quantity of water stored in the reservoir system is maximized. The operation of a reservoir sytem serving two or more of these purposes must take into consideration the trade offs that exist due to the conflicts in operating policies which maximize each purpose individually. The ultimate decisions concerning the operation of such a reservoir system must be made in the context of many economic and legal factors.

With the exception of flood control, the operation of a reservoir system is improved upon when avoidable water losses can be prevented. Evaporation is a significant water loss that has not been previously considered in the determination of reservoir system operating policies. As this study is directly concerned with evaporation losses in reservoir system operation, a brief overview of the evaporation process will be presented in the next section.

Evaporation Process

Evaporation is the process by which water is changed from the liquid to the vapor state. Evaporation will occur when molecules in the water body have sufficient energy to eject themselves into the surrounding atmosphere. Molecules may leave a solid surface in the same way; this process is called sublimation and is to be distinguished from evaporation. Water vapor molecules in the atmosphere surrounding the liquid water may also contain enough kinetic energy to penetrate the liquid surface, i.e., condense to the liquid state. The vapor pressures of the water body and surrounding atmosphere are a measurement of the kinetic energies contained therein. When the vapor pressures of the liquid water and water vapor are equal, the overlying atmosphere is said to be saturated, and no net evaporation occurs. The rate of evaporation is proportional to the difference in vapor pressures of the air and water; this fact was first recognized by Dalton and is now known as Dalton's Law.

The vapor pressures of both the water and air, and thus the rate of evaporation, are functions of temperature, wind, total dissolved solids content of the water and the shape of the water surface. An increase in temperature will increase the kinetic energy, and for equal increases in temperature of both the water and overlying air, a change in the evaporation rate may not occur. For large bodies of water, however, the corresponding changes in temperature of the air and water are unequal, and thus the evaporation rate will differ accordingly. Wind movement over a body of water will replace air which has already absorbed evaporated water with drier, less saturated air, resulting in an increase in evaporation. Wind speeds above the rate at which all of the moist air is replaced by drier air do not further increase the evaporation rate. The presence of dissolved solids in water decrease the vapor pressure of the water, therefore reducing the difference in vapor pressures of the air and water. Investigators have observed that evaporation proceeds at a faster rate from a convex surface than from a concave surface of water, although no one has quantified this phenomenon in equation form as yet. It is reasonable to expect that differences in the shape of reservoir water surfaces are negligible with respect to their influence on the rate of evaporation.

Evaporation Measurement

The determination of evaporation has been the subject of much research. All methods of evaporation determination are based on one of three fundamental approaches. These three approaches are the mass-transfer method, the energy-balance method and the water-balance method.

The mass-transfer method is based on the concepts of continuous and discontinuous mixing in the boundary layer which forms above the water surface. The method utilizes Dalton's Law which states that the rate of evaporation is proportional to the vapor pressure gradient which exists in the vapor blanket beneath the boundary layer. The energy-balance method makes use of the law of conservation of energy which states that the energy leaving via the water surface minus the energy entering the water is equal to the generation of internal energy within the water body. The energy utilized for evaporation is one of the components of the total energy leaving the water surface. Both the mass-transfer method and energy-balance method require the determination of parameters which are difficult to measure and necessitate the use of expensive equipment. Thus these methods have been appplied only in specific study locations, two of the more successful being at Lake Hefner, Oklahoma and Lake Mead, Nevada.

The water-balance method for evaporation measurement is simply an account of all inflows to and outflows from a reservoir, minus evaporation. Within a selected time period, the evaporation is equal to the net difference between the recorded inflows and outflows. Written in equation form, the change in storage can be expressed as follows:

$$\Delta S = Q - O - E \tag{I-1}$$

where ΔS = change in storage
Q = inflow
O = outflow
and E = evaporation.

Difficulties are encountered when attempting to apply this equation to actual reservoir sites. The change in storage within a selected time period can be calculated provided that accurate water surface elevations are recorded periodically, and corresponding storage-elevation data is available for the reservoir. The accurate measurement of total inflow to a reservoir is difficult since the reservoir may have several inflow sources, including precipitation. The measurement of outflow presents similar difficulties, in that outflow in the form of subsurface seepage is hard to quantify. Any error in measurement of the change in storage, inflow or outflow will result in an error in evaporation measurement. If the quantity of evaporation is small with respect to the other parameters, appreciable error can result in the determination of evaporation from only small errors in measurement of the other parameters.

The most practical, and the most widely used, method of evaporation measurement is the application of the water-balance method to specially designed evaporation pans. These pans, which come in a variety of standard sizes, consist basically of a shallow container of water made of galvanized iron which is placed in an open area in order to receive full sunlight. The only inflow to the pan is precipitation and, since there is no outflow, the change in storage is equal to the difference between precipitation and evaporation. Evaporation pans are located and monitored throughout the U.S. and provide a readily available source for obtaining evaporation data. Most of the available data is in the form of monthly average values. There are some records for which daily values are tabulated, although these are considered to be less accurate than monthly records.

By applying the water-balance method to both evaporation pans and neighboring reservoirs, it has been observed that the evaporation rate from the reservoirs average about 70% of the evaporation rate from the evaporation pans. This adjustment factor of .7 as applied to pan evaporation data is called the pan coefficient. A slight wind will have a much greater influence on the evaporation from a pan since much more of the saturated air can be moved away from the underlying water surface than for the actual reservoir. Also, the rate and time distribution of heat conduction to and from the pan is different from that of the reservoir, resulting in seasonal changes in the pan coefficient, the values ranging from .6 to .8.

Evaporation Reduction Studies

Earlier studies of evaporation reduction on a large scale focus attention on the application of surface films to storage reservoirs (Mansfield, 1953, Archer, et al., 1954, Harbeck, et al., 1959). The substances used have been certain types of parafinic chains of acids and alcohols. Basically, these substances are compounds of polar molecules and, when applied to a water surface, align themselves in such a way as to expose a surface film only one molecule thick. This monomolecular layer is thought to inhibit the transfer of water molecules from the water surface, thereby reducing evaporation.

Research in the field of surface films has tapered off recently, due to several major shortcomings in the method as a practical solution to the evaporation reduction problem. The presence of a surface film restricts the transfer of solar energy to and from the water and upsets the aquatic ecosystem existing in the lake. Wind movement over the water surface breaks up the film and reduces its effectiveness. Also, the cost of applying and maintaining surface films can exceed the expected benefits from the water thus saved.

Other possibilities for evaporation reduction from reservoirs have been mentioned (Freese, 1956; Frenkiel, 1965) in literature dealing with evaporation, although very little research has been devoted to such study.

One such possibility is the installation of covers over the surface of the reservoir. A fixed roof, floating rafts or windbreaks fall under this category. These types of covers are limited, of course, to small reservoirs. As with surface films, surface covers will have serious detrimental effects on aquatic life forms in the reservoir. Vegetative covers are another possibility, although their effectiveness would be reduced due to the transpiration of water from the vegetative cover itself.

Another possibility that has been considered lies in the recognition of the storage volume versus exposed surface area relationship at the reservoir sites. This can be a factor in both site selection studies and in multi-reservoir operational studies. It is well known that evaporation can be reduced at a reservoir site which exposes less surface area for the same storage volume as another reservoir site. Theoretically, it is possible in a reservoir system to release water from each reservoir in such a way as to minimize the total exposed surface area. The effectiveness of such a method of evaporation reduction will depend on the nature of the storage-area relationships of each reservoir and the flexibility of water transfers between the reservoirs in the system.

Evaporation reduction must be considered with respect to its effect on the important functions of the reservoir system. If, in order to reduce evaporation, the ability of the reservoir system to fulfill its purpose is impaired, then it can be concluded that evaporation reduction is not a worthwhile consideration. It may be argued, however, that in times of severe drought or due to increased water needs, evaporation reduction may be economically justified in some water supply systems.

Fundamentally, evaporation losses must be viewed as a part of the overall objective of water conservation in general. In reservoir systems where other forms of water losses, such as spill or seepage occur in large quantities, all of these water loss components must be considered if the objective of water conservation is to be truly met. Evaporation losses, however, may be viewed as being a more severe type of water loss than the other kinds of major reservoir losses, ie., spill and seepage. As water evaporates, it returns to the atmospheric component of the hydrologic cycle, and may not appear in a usable form again for some time. Spill and seepage losses, on the other hand, still remain at or near the earth's surface where they may be used before they return to the ocean or atmosphere. Furthermore, evaporated water is in its purest form, leaving behind any impurities which may have been contained in it. This is not the case for water which is spilled downstream or which infiltrates into groundwater aquifers. Water loss due to seepage may, in fact, be enhanced in quality as it moves through the groundwater aquifer.

It is well recognized that evaporation losses occur in any reservoir or water supply system. Much research has been devoted to improving ways of measuring evaporation and techniques by which evaporation can be reduced using monomolecular surface films. Evaporation reduction by other techniques, particularly surface area minimization, have yet to be studied, even to the extent of showing that they do or do not warrant further in-depth research. It is probable that certain combinations of reservoir system hydrologic and geographic characteristics will prove to have more potential for evaporation reduction than others. Research directed towards categorizing these reservoir system characteristics with respect to evaporation reduction may prove to be of some beneficial use for future research into evaportion reduction at selected locations.

Purpose of Research

It is the purpose of this study to investigate evaporation reduction in a multi-reservoir system by the method of surface area minimization. For the purposes of this study, the means by which this will be accomplished is by selection of different release policies from each reservoir, thereby varying the total surface area so exposed. The optimal policies are those which minimize the total surface area. First, a dynamic programing model, developed specifically for this research, will be presented which minimizes evaporation by surface area reduction for a two-reservoir system. The basic principles governing surface area reduction will then be discussed in the context of how they determine a release policy to minimize evaporation losses. The model will then be applied at selected geographic locations, involving differing physical and hydrologic reservoir system characteristics, in order to determine the potential for evaporation reduction at these locations.

The underlying goal of evaporation reduction is, of course, water conservation. Thus, evaporation reduction will be evaluated in relation to its effect on reservoir system spill. The importance of evaporation reduction in each geographic location will be determined by a) quantifying evaporation and spill losses, and b) evaluating reservoir system firm yield.

This study will conclude with an investigation of the effects of selected reservoir system physical and hydrologic characteristics on evaporation reduction and overall water conservation. These characteristics include reservoir inflows, shapes, evaporation rates and yield quantities.

CHAPTER II
MODEL DEVELOPMENT

Model Selection

At present, there are numerous computer programs in existence which simulate reservoir operation. Many of the more recent models employ some type of optimization scheme to determine operating policies which best satisfy a desired objective. Although some of the optimization models for reservoir systems include the estimation of evaporation as a term in the mass balance equation for each reservoir, the role of evaporation losses as an integral part of optimal reservoir system operation has yet to be fully investigated.

Prior to the actual development of the computer program used in this research, it was necessary to determine the specific objectives to be met by the model and the available means by which these objectives can be met. As mentioned previously, the primary objective of evaporation reduction is to be achieved by altering the release schedules of each reservoir in the system such that the total quantity of water entering and leaving the system can be stored in such a fashion as to minimize the exposed surface area.

Because of the large number of factors which foreseeably determine the optimal reservoir system release schedule and the ad hoc nature of multi-reservoir system research, no usable guidelines or criteria could be formulated to preselect a system release schedule which would guarantee that optimal system regulation has been met. In consideration of this seeming limitation the alternative approach would be to develop a computer model to efficiently evaluate a sufficient number of alternative release schedules and select the one which is optimal in terms of the primary objective, i.e., evaporation minimization. Of the available techniques to handle just such a task, the method of dynamic programming (DP) is the most suitable. This approach to optimization problems has recently been widely used in reservoir system applications. Its theory and principles of application have been discussed extensively in the literature (Bellman, 1957; Nemhauser, 1966) and thus only a brief description of its logic followed by some relevant applications in reservoir system management are presented here.

Dynamic Programming Description

Basically, DP is a multi-stage decision-making process. Problems amenable to DP application can be separated into a finite number of stages, each of which requires a decision to be made over a number of possible choices or states. The relative merit of each decision at each stage will uniquely determine the optimal decision to be made at each stage. The method by which the relative merit is evaluated is, of course, unique to each problem situation. The key principle of DP, and the one which has proven its usefulness, is that at each stage in the decision making process, the optimal decision to arrive at the next stage depends only on the particular state at that stage, and not on the decisions made at previous stages. In mathematical notation, the optimal decision to be made at stage n from state s is expressed by the following recursive equation:

$$f^*_n(s_n) = \underset{x_n}{\text{optimal}} \; C_{s_n,x_n} + f^*_{n-1}(s_n) \qquad \text{(II-1)}$$

where

n = stage location

s_n = state location at stage n

x_n = decision at stage n-1 to arrive at stage n

$f^*_{n-1}(s_{n-1})$ = cumultative sum of each decision value for the optimal policy through stage n-1 at state s_{n-1}

$C_{s_n x_n}$ = decision value associated with selection of x_n at state s_{n-1}

$f^*_n(s_n)$ = cumulative sum of each decision value for the optimal policy through stage n.

At stage n-1 given state s_{n-1} and decision x_n, s_n is uniquely produced by a transition function, denoted by $T(S_{n-1}, X_n)$. Thus the following relationship holds between the decision variable x_n and the initial state, s_{n-1}

$$s_n = T(s_{n-1}, x_n). \qquad \text{(II-2)}$$

The decision value associated with the selection of x_n at state s_{n-1} is determined using what is called the return function. Thus

$$C_{s_n x_n} = R(S_{n-1}\ x_n) .$$

In order to see just how using DP would prove to be more efficient than simply a trial and error approach, consider the following example: A four stage problem, with four possible states at each stage would entail the comparison of 4^3, or 64 possible ways of making a series of four decisions, one (or more) of which being the optimal set of decisions. With DP, only the optimal decisions at each of the four states between each stage need be recorded, thus only 12 sub-optimal series of decisions are to be compared to find the optimal set.

The optimal selection over all x_n can either be a minimum or a maximum sum, depending on the particular problem formulation. The notation as presented in Equation II-1 examines each stage in succession, beginning from the first stage. Contrary to the notation used herein, it has been customary to present the above formulation in a form which begins from the last stage, as some DP problems are tractable only when analyzed in this fashion.

Application of Dynamic Programming in Reservoir Operation

The stage-by-stage analysis as expressed by Equation II-1 forms the basis of an algorithm suitable for computer programing and which is applicable to a wide variety of problem types. Many water resources problems, which typically involve the distribution of water over a series of time periods, have been analyzed using DP techniques. Of particular interest in the context of this research are reservoir management problems which utilize DP techniques and which take into consideration evaporation losses as a factor in determining the optimal operating policy.

Collins, 1977, considered evaporation losses in a multi-reservoir system operated by the city of Dallas, Texas. Evaporation from each reservoir was estimated by assuming a constant evaporation loss for every time period. System operations, such as water treatment, water purchase, etc. were all assigned monetary costs and the system was modeled using a DP algorithm. A cost was also assigned to evaporation losses and in this way evaporation was reduced within the context of minimizing overall operating costs.

Tauxe, 1979, examined evaporation losses in a somewhat different context. He used DP to study the tradeoff between minimizing cumulative evaporation and maximizing cumulative dump energy for a single reservoir. Evaporation losses were approximated by 31 discrete values, specified as a function of storage. As might be expected, it was found in this study that the minimization of evaporation required that the reservoir surface area be kept as small as possible, which resulted in a minimzation of reservoir storage. Thus the available water for dump energy was likewise reduced.

Other pertinent research examples are those of Harboe, Mobasheri and Yeh, 1970, Trott and Yeh, 1972, and Fults, Hancock and Logan, 1975. Harboe, et al., examined the optimal operational modes of a multi-purpose reservoir. They used a DP model which calculated evaporation based on the average area of the reservoir for each individual time period. Trott and Yeh used DP to determine the optimal sizes of proposed reservoirs within a system. Evaporation losses were estimated using a constant loss for each reservoir for each time period. Fults, et al., studied a four-reservoir system which serves as an integral part of the Central Valley Project in California. The DP model used determines an optimal water and power schedule for the four reservoirs. Similar to Harboe, et al., monthly evaporation is calculated for each reservoir using the average storage for each month of the study period.

Dynamic Programming Model Applicability

In the case of reservoir operation studies employing DP techniques of analysis, it is necessary that, in order to solve the transition function between successive stages, the inflow sequence to the reservoirs must be known beforehand. As will be explained later in Chapter IV, one of the constraints on the transition function is the mass balance equation for the storage contents of the reservoir, one of the variables of which is inflow. This is unrealistic in the sense that, in actual reservoir operation, future inflows are not known. Researchers have attempted to alleviate this shortcoming by using sequences of historical inflows which represent drought conditions or basing conclusions on a number of different sets of historical inflows. Some research has been devoted to the application of stochastic DP, where the inflows are expressed in terms of the probability of their occurence.

The use of DP with its inherent requirement of future inflow knowledge is justified in this study for three reasons. First, the model was intended to be used as a method of analysis with which the potential for evaporation reduction can be determined, and not as a guide for actual reservoir operation. Second, the use of an optimization model for the objective of evaporation minimization produces the operating policies whereby the objective is realized. These operating policies, along with the amount of water saved by their implementation, can be viewed in regard to their compatibility with established reservoir operation guidelines. The third, and most important reason is that an optimization approach provides a means by which evaporation losses can be considered as a factor in the formulation of operating policies for the objective of water conservation.

Reservoir Mass Balance Equation

Reservoir operation models require that the analysis of the system parameters be done at discrete intervals in time. Choosing the time intervals as months has proven to be the most practical since monthly data are readily available and a monthly release schedule is reasonable for actual reservoir system regulation. Time intervals smaller than one month can provide additional information only to the extent that the hydrologic data used is accurate. The total quantities of inflow and outflow which occur during one month are added to the beginning of the month storage to determine the end of the month storage, as expressed by the following mass balance equation:

$$S_{n,f} = S_{n,i} + Q_n - O_n \qquad \text{(II-3)}$$

where $S_{n,f}$ = final storage, month n

$S_{n,i}$ = initial storage, month n

Q_n = total inflow during the month n

O_n = total outflow during the month n.

Both the inflow and outflow are expressed in volume units commensurate with the storage quantities since they occur over a specific time interval.

For the purposes of this study the total outflow from the reservoir is separated into its two major components - downstream release and evaporation loss from the water surface. The release may be either as required to meet downstream demands or it may be spill in excess of reservoir maximum storage. Other types of losses are not considered for they are assumed to be negligible with respect to the major outflow components as described. One of the losses not considered is seepage from the reservoir into the surrounding subsurface soil strata. Another loss not considered is evaporation and transpiration from the banks of the reservoir when it is less than full, although this loss may be approximately accounted for depending on the method of lake surface evaporation used. These minor losses would be most difficult to measure if it is desired to include them in the mass balance equation. The resulting mass balance equation is written as shown below:

$$S_{f,n} = S_{i,n} + Q_n - E_n - R_n - SP_n \qquad \text{(II-4)}$$

where

E_n = evaporation loss during month n

R_n = release during month n to meet downstream demands

SP_n = spill during month n.

Evaporation Determination

Monthly evaporation calculations in the model were based on lake surface evaporation rates per unit surface area. These evaporation rates were determined from pan evaporation data and pan coefficients, and were obtained from various hydrologic publications.

For reservoir systems analysis, evaporation rates represent the difference between gross evaporation and effective rainfall. The effective rainfall is the amount of rainfall which fell on the reservoir site that offsets the evaporation loss, less the amount that has run off and thus is included in the reservoir inflow records. For the purposes of this study, all of the monthly rainfall is considered to be effective in offsetting the monthly evaporation loss, and therefore the monthly inflows used do not include runoff from rainfall which fell on the reservoir site.

The evaporation rate times the average surface area for the month yields the evaporation quantity (expressed as a volume of water) for the month.

$$E_n = e_n \bar{A}_n \tag{II-5}$$

where

e_n = evaporation loss rate per unit area, month n

$\bar{A}_n$ = average surface area for the month n.

$\bar{A}_n$ is determined by a linear average of the storage contents as follows:

$$\bar{A}_n = \frac{f \quad S_{n,i} + S_{n,f}}{2} \quad . \tag{II-6}$$

The function f is expressed in tabular form as pairs of storage-area values. Most reservoir sites exhibit a nonlinear relationship between the storage and surface area, especially in the lower portions of the reservoir. Calculation of the average area based on a linear average of the storage contents may appear to be inaccurate; however, it is reasonable when the approximations concerning inflow and release are considered. Because the mass balance equation is solved at monthly intervals, whatever variations in inflow and release that can occur during the intervening time period cannot be accounted for. For example, a reservoir may receive the major portion of its inflow during the first few days of the month, in which case the actual average monthly storage (and average area) would be higher than the linear average of the initial and final values.

Model Description

The computer program developed for this research utilizes a dynamic programing algorithm to determine the optimal operating policy for a specified sequence of monthly time periods. The objective of minimizing cumulative evaporation is to be met via reservoir system release regulation. The regulation of reservoir releases is done in such a way as to expose the minimum cumulative surface area of all of the reservoirs in the system over the time period under consideration.

More generally, the objective is to minimize the cumulative surface area times the evaporation rate (per unit area) of the reservoirs in systems where the evaporation rates are different for each reservoir. In accordance with optimization principles it is the cumulative sum of evaporation which is to be minimized and hence, for any given portion of the time period, the system may not be operating to minimize evaporation within that portion, but rather to minimize evaporation over the entire time sequence.

The program is limited to simulating the operation of a two-reservoir system, as it was decided that a two-reservoir system would be flexible enough in reservoir release options to show evaporation reduction potential and the types of operating policies necessary to achieve it.

It was anticipated that evaporation minimization should be considered in relation to its effect on the other major source of water loss, i.e., reservoir spill. Thus the model was given the capability of determining the operating policy for one of two additional objective functions: minimizing cumulative spill and minimizing cumulative total water loss, the total water loss being the sum of evaporation and spill.

The computer model, hereinafter referred to as RESEVAP, is designed to simulate the operation of the two-reservoir sytem in either of its two possible configurations - parallel or series. In the case of the series configuration, the upstream reservoir is designated as Reservoir 1 and the downstream reservoir as Reservoir 2. Both sytem configurations require that the total release from the sytem for a given month, excluding spill, must equal the specified demand for that month. Figures II-1 and II-2 depict System I and System II, respectively.

For convenience, the three objective functions and the two system configurations will be denoted as follows:

Objective 1 - minimize cumulative evaporation
Objective 2 - minimize cumulative spill
Objective 3 - minimize cumulative total water loss
System I - reservoirs in parallel
System II - reservoirs in series
Reservoir 1 - upstream reservoir (for System II)
Reservoir 2 - downstream reservoir (for System II).

The specified monthly demand can be thought of as a firm water requirement, in that no system release less than this quantity can be tolerated, nor can any release in excess of this quantity be effectively used. Only in the situation where there is no available storage in the reservoir system can the total release from the system exceed the demand. It is assumed that the two-reservoir system does not serve any further downstream demands other than the specified monthly demand. Thus any system spills are considered as a loss from the system, and no benefits can be obtained therefrom, just as with evaporation losses.

The reservoirs in series system configuration essentially permits releases in excess of the demand from the upstream reservoir and thus the transfer of water in storage from the upstream reservoir to the downstream reservoir. The release from the downstream reservoir must necesarily be equal to the demand. For time intervals of one month, the lag time involved in the transfer of water from

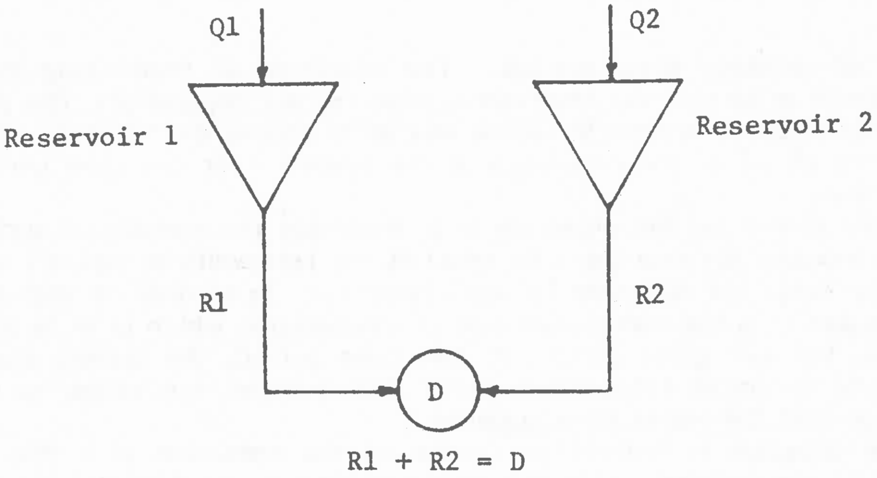

Figure II-1

System I (reservoirs in parallel)

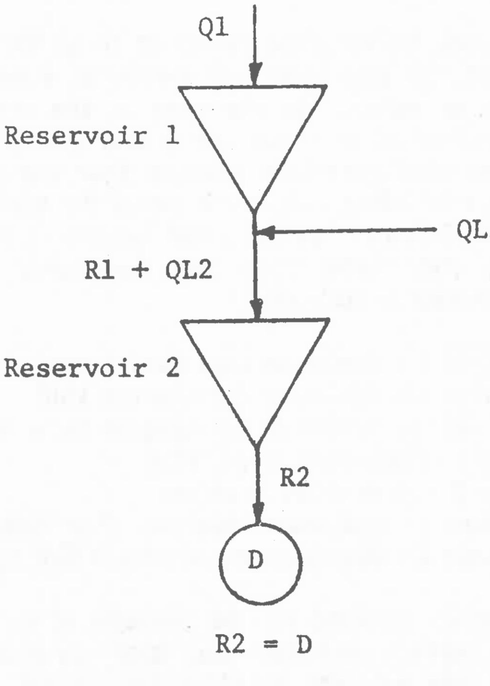

Figure II-2

System II (reservoirs in series)

Reservoir 1 to Reservoir 2 is small and can be ignored in this study. Also, any evaporation or seepage losses occuring in the water course between the reservoirs are not taken into consideration. In the cases of the parallel configurations, no transfer of water is permitted between the two reservoirs and the sum of the releases from both reservoirs must equal the demand.

Data Input Description

Hydrologic and physical data input describing the reservoir system consists of initial storage for Reservoirs 1 and 2 and, for each monthly time period, inflow to Reservoir 1, intermediate inflow to Reservoir 2 (excludes outflow from Reservoir 1 for the Sytem II configuration), downstream demand, evaporation rates, and minimum and maximum storage levels for both reservoirs. Inflows are specified in cfs-days, as they are available in this form directly from the U.S.G.S. streamflow records. The monthly demand and reservoir storages are specified acre-feet. Evaporation rates are specified in inches per unit surface area. The specification of minimum and maximum storage levels for each month allows flexibility in defining the amount of conservation storage available during each month. The surface area as a function of storage relationship at each reservoir is defined by a selected number of pairs of storage and corresponding area values, from zero storage to maximum pool storage. Surface area values are specified in acres.

In the situation of the reservoirs in series configuration (System II), it may be unreasonable to allow unlimited release from the upstream reservoir. Therefore, the ratio of release to demand is not allowed to exceed a specified value, RD1 (IT), for each month IT. For the reservoirs in parallel configuration (System I), RD1 (IT) = 1 for all IT. For System II, RD1 (IT)$\geq$1, for all IT. The array RD1 is a dimensionless quantity also entered as data input for each monthly time period.

Dynamic Programming Algorithm Description

The variables and notation defining the dynamic programing algorithm are as follows:

Algorithm variables -

E1 = evap., Res. 1

E2 = evap., Res. 2

NS = total number of states

NT = total number of stages

Q1(IT) - inflow, Res. 1

RD1(IT) = ratio, release to demand

R1 = release, Res. 1

S1(I) = beginning-of-month storage, Res. 1

S1(J) = end-of-month storage, Res.1

SP1 = spill, Res. 1

SP2 = spill, Res. 2

Stage - monthly time periods

IT; IT = 1, 2, ..., NT.

Objective function - one of three possible choices:

1) minimize cumulative evaporation

$$\text{Min} \sum_{i=1}^{NT} (E1_i + E2_i)$$

2) minimize cumulative spill

$$\text{Min} \sum_{i=1}^{NT} (SP1_i + SP2_i)$$

3) minimize cumulative sum of evaporation plus spill

$$\text{Min} \sum_{i=1}^{NT} (E1_i + E2_i) + (SP1_i + SP2_i) \quad .$$

Discretized state variable - beginning-of-month storage in Reservoir 1

SI(I); I = 1, 2, ..., NS.

Discretized decision variable - end-of-month storage in Reservoir 1

S1(J); J = 1, 2, ..., NS.

Return function - one of three possible forms, depending on the selected objective function

1) $R\left(S1(I), S1(J)\right) = E1 + E2$ (II-7a)

where the function f is composed of the mass balance equations for Reservoir 1 and Reservoir 2, solved for E1 and E2, respectively.

2) $R\left(S1(I), S1(J)\right) = SP1 + SP2$ (II- 7b)

where f is solved for the spill in Reservoirs 1 and 2

3) $R\left(S1(I), S1(J)\right) = (E1 + E2) + (SP1 + SP2),$ (II-7c)

where f is solved for both evaporation and spill for Reservoirs 1 and 2.

Transition function - The decision value at stage IT is the beginning-of-month storage at stage IT + 1

$T\left(S1(I), S1(J)\right) = S1(J).$ (II-8)

The constraints on the selection of the decision variable value, S1(J), are evaluated using the mass balance equation (eq. II-4), and the ratio of release to demand. They are

$$R1 \geq 0 \qquad \text{(II-9a)}$$

where $R1 = S1(I) - S1(J) + Q1(IT) - E1$

and $$R1/D(IT) \leq RD1\,(IT)\,. \qquad \text{(II-9b)}$$

The restriction that the system release should equal the demand for any given month uniquely defines the release for Reservoir 2, R2, once the mass balance equation for Reservoir 1 is solved for R1 for a selected end-of-month storage, S1(J). With Q2 and now R2 known E2, and thus S2, can be solved for by an iterative process using the mass balance equation for Reservoir 2. The selection of the release from Reservoir 1, in essence, requires only a single state variable, i.e., the end-of-month storage in Reservoir 1. Furthermore, the mass balance equation is exactly satisfied for each month at each reservoir by using the end-of-month storage as the decision variable.

The state variable is discretized into a selected number of values, ranging from maximum to minimum storage for Reservoir 1. These values are entered as data input into an array S1. Thus, the storage in Reservoir 1 may take on only these discrete values, while the storage in Reservoir 2 is a floating variable, depending on the selection of the end-of-month storage in Reservoir 1.

Appendix A contains a list of variables for the computer program RESEVAP. Appendices B and C contain, respectively, a flow chart and program listing of RESEVAP.

The basic program algorithm is as shown in Figure II-3:

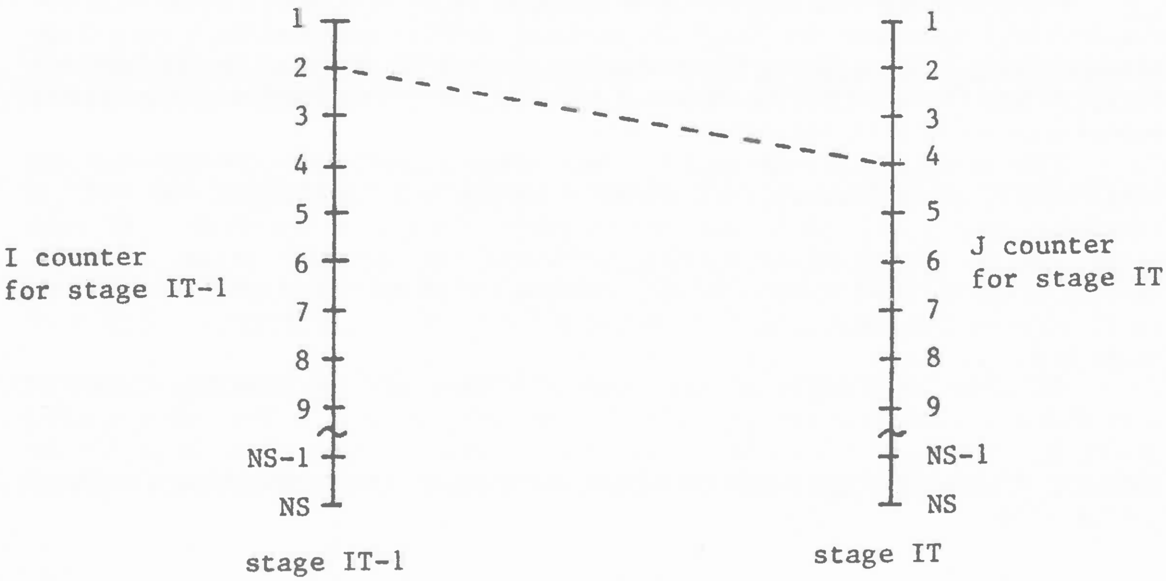

Figure II-3
Discretized Storage Levels, Reservoir 1

Between two successive stages IT-1 and IT, all possible combinations of storages at stages IT-1 and IT are evaluated. The combination S1(2) to S1(4) is shown in Figure IV-3. Beginning with the first value for the final storage, S1(J) where J=1, each feasible value of the initial storage, S1(I), I=1, ..., NS, is used to calculate the corresponding evaporation, E1. The mass balance equation is then solved for the release, R1. If the release is less than zero, then the selection of S1(J) was too large, and the next lower value is chosen.

For a non-negative R1, R1/D(IT) is compared to the value RD1(IT) and, if less than RD1(IT), the release R1 is feasible, as far as Reservoir 1 is concerned. If R1/D(IT) is greater than RD1(IT), then for the same S1(J) the next lower S1(I) is selected, as this will result in a smaller release, R1.

For a feasible R1, and according to System I or System II specifications, spill from Reservoir 1 and inflow to Reservoir 2 are calculated. The resulting end-of-month storage and evaporation for Reservoir 2 are then determined by iteration, using Equations II-4, II-5 and II-6. If the final storage, S2, so calculated is less than the minimum storage allowed, Reservoir 2 was incapable of supplying the release R2, and thus the value of R1 must be increased. Therefore, the next lower value of S1(J) is selected and the algorithm repeated.

For each feasible storage level S1(I) at stage IT-1, the sub-optimal policy up to stage IT is found for Objective 1 by adding the cumulative sum of evaporation up to stage IT-1 to the total evaporation for decision S1(J), stage IT, which is E1+E2. The decision yielding the minimum sum of these two terms for a given state I is then indexed, and its total cumulative evaporation is stored in the array ESUM. For Objective 2, spill replaces evaporation as the objective function parameter. For Objective 3, the objective function parameter is the sum of evaporation plus spill. The array SPSUM and the sum of the arrays ESUM and SPSUM store the cumulative values for Objectives 2 and 3, respectively.

For infeasible trial selections of decision S1(J) for a given state S1(I), the cumulative evaporation for stage IT, decision S1(J) is assigned to a very large number, 1×10^{12}. Thus during the evaluation process for the next month (between stages IT and IT+1), infeasible values of S1(I) are those associated with cumulative evaporation equal to or greater than 1×10^{12}.

This procedure is repeated for each stage in succession through the last stage where, in accordance with dynamic programming principles, the optimal operating policy, defined by the end-of-month storage in Reservoir 1 at each stage, can be identified by tracing backwards through each stage. Finally, optimal stage variable values (storage, release, evaporation and spill) are recovered by applying the mass balance equation to Reservoir 1 and Reservoir 2 at each stage in succession.

If, after evaluation of any stage IT, there are no resulting values of cumulative evaporation for any state J, then the situation is that no operating policy between stages IT-1 and IT was able to release enough water to satisfy the demand. Thus a shortage has occured and the program stops and prints a message to that effect.

Objective Function Considerations

The objective of minimizing cumulative spill presents difficulties during periods of no system spill. At a given stage n for which no spill has occurred at all stages up to n, the value of the return function (system spill) will be zero for any feasible policy selection. Thus, the DP algorithm cannot effectively make a decision based on the objective function. The choices made at these periods of no cumulative spill can effect, to varying degrees, the final value of the cumulative spill, assuming, of course, that spill does occur during future periods.

Consider the following example situation: Two reservoirs in parallel are modeled using five years of selected inflows and demand requirements. Reservoir 2 is subjected to a series of large inflows after two and one-half years which more than exceeds its capacity, even when empty. At this same time, Reservoir 1 receives only small inflows. For the first two and one-half years, if an operating policy was selected which kept most of the stored water in Reservoir 2, certain quantity of spill would necessarily occur at Reservoir 2. If, however, a policy was selected for the first two and one-half years which kept most of the stored water in Reservoir 1, then the spill at Reservoir 2 would be reduced. Also, a policy which maximized the evaporation losses at Reservoir 2 would allow more storage space for the large inflow into the reservoir. Without modification, neither of these policies can be selected by applying the objective of minimizing the cumulative spill. Certainly the policy which maximizes the evaporation loss would be contrary to the overall objective of conserving water.

In situations of no cumulative spill, the objective function of minimizing spill cannot be relied upon to select a sub-optimal policy which will result in an absolute minimum value of spill occurring at future stages. Once an arbitrary sub-optimal policy is selected, however, the algorithm can minimize the spill occurring at future stages in keeping with the sub-optimal policies chosen at earlier stages for which no spill occurred. In accordance with the overall objective of conserving water, an additional objective has been incorporated into the DP algorithm for the cases when the feasible decision variable options result in the same value of the objective function of minimizing cumulative spill. This additional objective, upon which the selection of the decision variable is based, is to select the policy which results in the smallest value of cumulative evaporation. In essence, the inclusion of this additional objective therefore requires that the objective of minimizing cumulative spill will be met within the context of minimizing the total water loss. During periods when several policies produce the same optimal value of cumulative spill, a selection will then be based on minimizing the total water loss from the system, i.e., the sum of spill plus evaporation.

The additional objective of evaluating the total cumulative water loss in situations of equal objective function values is also incorporated into the objective of minimizing the cumulative evaporation. It is anticipated that the occurence of several policies producing the same quantity of evaporation is unlikely. However, should this occur, the policy which yields the smallest value of cumulative spill will be selected.

As discussed earlier, the policy which results in the absolute minimum of cumulative spill is the one in which, during extended periods of no spill, stores the inflow in such a way as to maximize the available storage for future inflow. In this context it is recognized that the additional objective of minimizing evaporation in such a situation may not maximize the available storage for future inflow. In actual reservoir operations, uncertain knowledge concerning the magnitude and distribution of future inflow suggests that a policy which attempts to maximize the available storage rather than to maximize the quantity of water stored is unsound. Therefore, the additional objective of minimizing the total water loss, which in effect maximizes the water stored, is thought to be logical and consistent with the underlying effort to conserve water.

State Space Discretization

The discretization of the storage space for Reservoir 1 must be given careful consideration when preparing a set of input data. An increment between states which is approximately equal to or greater than the demand quantity will, in all probability, result in no feasible policies during some months. Consider the following example:

$$D = 1000 \text{ acre-feet}$$

$$\Delta S = 1500 \text{ acre-feet}$$

$$Q1 = 320 \text{ acre-feet.}$$

Initially, let $S1(I) = 10{,}000$ acre-feet. A reasonable value for E1 is about 20 acre-feet. Solving the mass-balance equation for R1 we have

$$S1(J) = 10{,}000 + 320 - R1 - 20$$

so

$$R1 = 10{,}000 - S1(J) - 300$$

For a feasible policy (for System I) it is required that $R/D \leq RD1$, where $RD1 = 1.0$.

Thus the conditions for feasibility are

$$R1 = 10{,}000 - S1(J) - 300$$

subject to

$$0 \leq R1 \leq 1{,}000.$$

Selecting the neighboring values of S1(J) of 11,500; 10,000 and 8,500 acre-feet, none of the ensuing values for R1 are feasible, and it is obvious that no other selection of S1(J) would be feasible either. In this situation feasible policies may only be obtained if the state increment, ΔS, is less than the demand. It is true that for System II the second constraint on R1 becomes $R1 \geq 0$, since RD1 may be much greater than 1.0. However, the large state increment relative to the demand may still result in policies which are infeasible, based on conditions at either Reservoir 1 or Reservoir 2.

The state space should also be discretized with regard to the degree of accuracy desired and the computer time required to achieve it. It can be said that any optimal operating policy is the absolute best with respect to the objective function, plus or minus the state increment. That is, the final storages in each reservoir are optimal within $\pm\Delta S$, as storages between discrete values at Reservoir 1 were not evaluated.

Program Execution Time

Figure II-4 shows the total execution time for the program on a CDC Dual Cyber 170/750 computer as a function of the number of states. These runs were made for 120 time periods. For a state space discritization of NS values, the total number of policies to be checked for feasibility between successive stages is NS^2. For an increase in the state space to NS+1 values, the additional number of policies to be checked for feasibility between successive stages is

$$2\ NS + 1.$$

For NT time periods, the total number of additional trial policies that must be checked is thus

$$NT\ (2\ NS + 1).$$

For an increase in the number of time periods to NT+1, the total number of additional trial policies to be checked is NS^2.

In general, if the number of time periods is at least one-half the total number of states, NS, then an enlargement of the size of the state space will increase the execution time faster than an equal enlargement of the number of time periods.

For a test run with NT time periods and NS possible state values, the total number of trial policies that must be checked for feasibility is $NT\ (NS)^2$. Just how many of these trial policies are feasible and thus must be evaluated is determined by a number of factors, the most important being the relative size of the demand quantities, D(IT) and the state space increment. For a very small state space increment, there would conceivably be many feasible operating policies between successive stages. As discussed previously, a larger state space increment will result in fewer feasible policies, with the extreme case of no possible policies which can satisfy the mass balance equation at each reservoir. Other factors determining the number of feasible policies are the size and distribution of inflows and the maximum allowable storage in each reservoir.

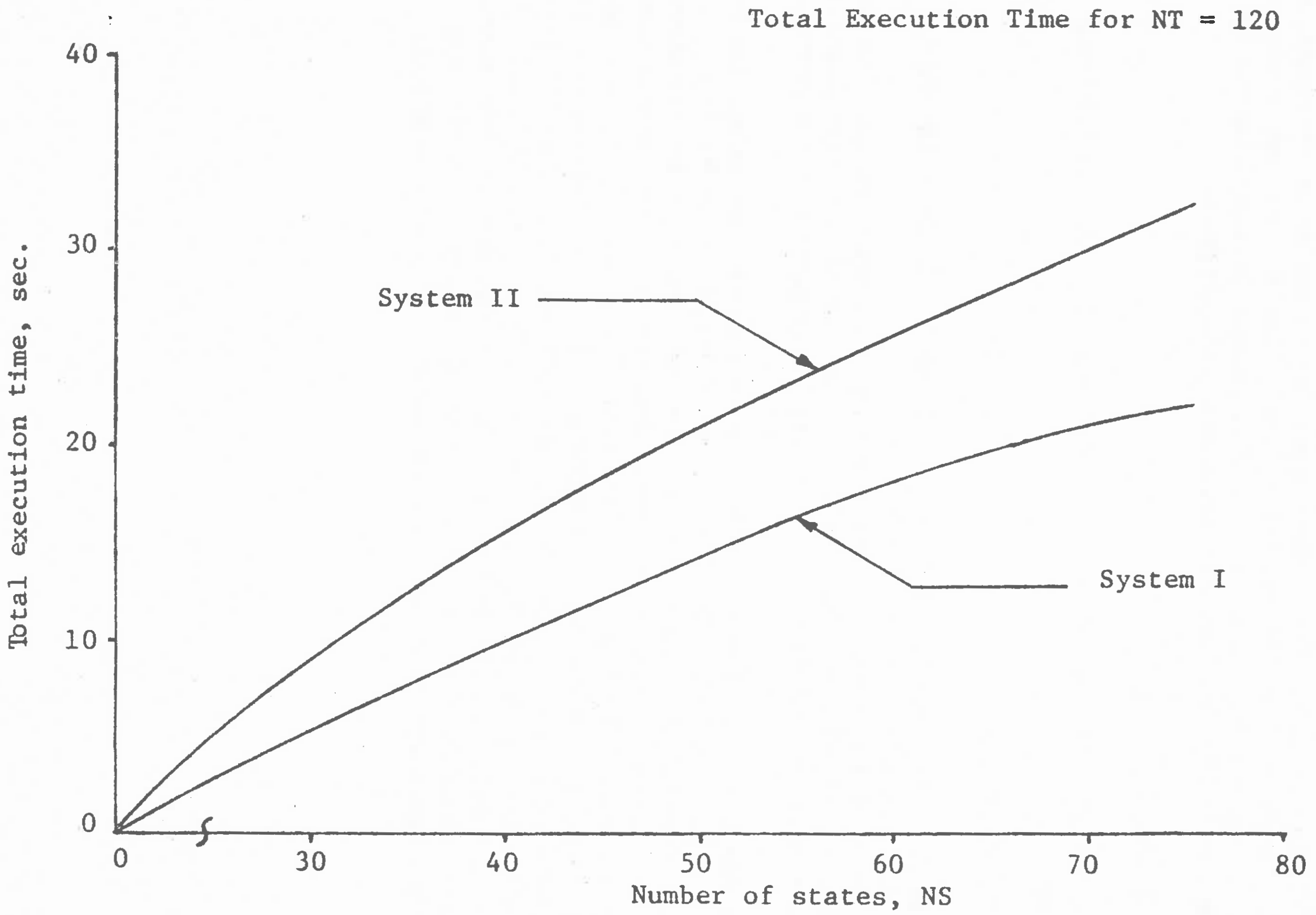

Figure II-4

Total Execution Time, Program RESEVAP

CHAPTER III
THEORY OF EVAPORATION REDUCTION VIA RELEASE REGULATION

Underlying Principles

The two-reservoir system as modeled by RESEVAP simulates evaporation losses as a function of surface area only. Thus, the primary concern in attempting to reduce evaporation in such a multi-reservoir system via release regulation is to make the required releases from the reservoirs in such a way as to minimize the total exposed surface area. At first glance, it might seem reasonable to expect that the means by which this can be accomplished is to simply release the water from the reservoirs with the largest surface areas. However, more careful consideration suggests that the reservoirs with the largest rates of change of area (with respect to storage), not the largest areas, should be released from first. A given quantity of water released from the reservoir system will result in the greatest reduction in area when released in such a fashion, provided the evaporation rates are the same for both reservoirs.

Investigating this idea further, consider the mathematical representation of a hypothetical reservoir shape, an inverted right circular cone, as shown in Figure III-1.

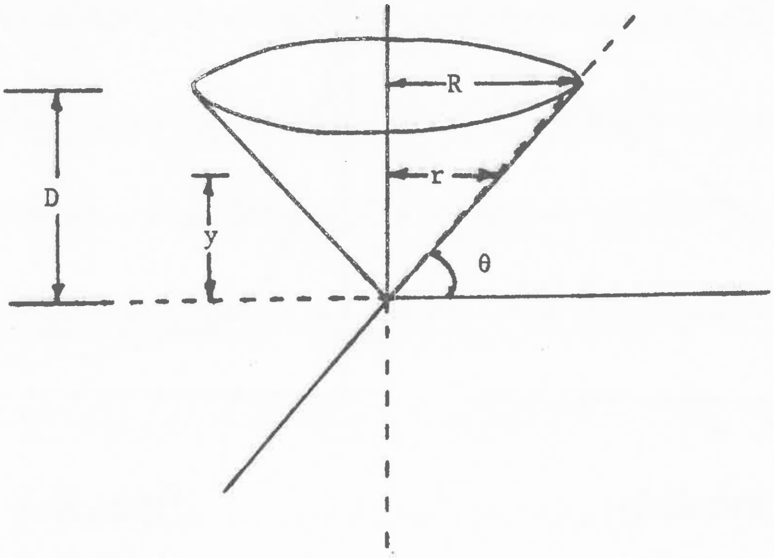

Figure III-1

Hypothetical Reservoir Shape

The surface area, A_s, and volume, V are written respectively as

$$A_s = \pi r^2 = \pi \frac{y^2}{(\tan\theta)^2} \qquad \text{(III-1a)}$$

$$V = \frac{1}{3}\pi r^2 y = \frac{1}{3}\pi \frac{y^3}{(\tan\theta)^2} \qquad \text{(III-1b)}$$

where y = depth ; $0 \lesssim y \lesssim D$

r = radius at depth y ; $0 \lesssim r \lesssim R$.

Taking the ratio of the derivatives dA_s/dy and dV/dy gives

$$\frac{dA_s/dy}{dV/dy} = \frac{2\pi y/(\tan\theta)^2}{\pi y^2/(\tan\theta)^2}$$

or

$$\frac{dAs}{dV} = \frac{2}{y} \, . \qquad \text{(III-1c)}$$

So, as the depth y (and thus the volume) increases, the value of dA_s/dV will decrease in proportion. Sketches of A_s and dA_s/dV versus V are shown in Figures III-2a and III-2b below.

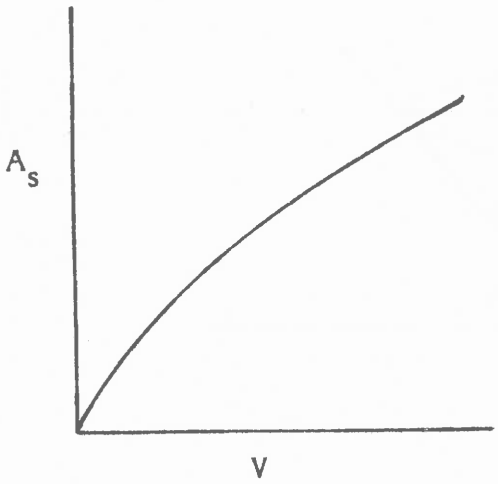

Figure III-2a

A_s vs. V

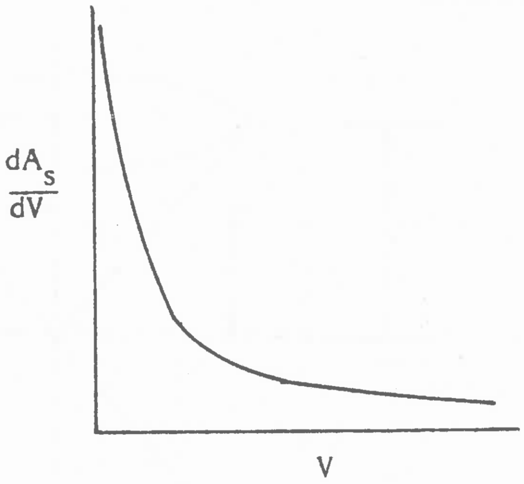

Figure III-2b

dA_s/dV vs. V

Actual reservoir shapes, of course, are not smooth shaped surfaces like that of a right circular cone. However, a plot of reservoir surface area versus storage shows the same general form as that of Figure III-2a. Of the many reservoir storage-area curves encountered in the course of this research, all of them exhibited characteristics similar to that of Figure III-2a. From about half full to maximum storage, most of the reservoirs investigated showed a nearly linear relationship between storage and area.

Verification of Theory

Because of the similarity between actual reservoir storage-area curves and that of Figure III-2a, it is also a fact a plot of $\Delta A/\Delta S$ for an actual reservoir will result in a curve resembling Figure III-2b. This implies that as the storage contents decrease, the rate of change of area with respect to storage will correspondingly increase. Consider the application of this principle to a two-reservoir system, both reservoirs of the same identical shape and initial storage contents. For a given amount of water to be released from storage, the selection of either reservoir as the one from which all the water shall be released will result in its value of $\Delta A/\Delta S$ to be higher than that of the other reservoir, after the release has been made. Thus it follows that any subsequent releases should also be made from this same reservoir, as its value of $\Delta A/\Delta S$ will keep on increasing to a maximum value when it becomes empty. That this "principle of continuous release," i.e., releasing from the reservoir with the highest value of $\Delta A/\Delta S$, results in the minimum amount of evaportion loss is shown in the example to follow:

Let $g_1 = \dfrac{dA_1}{dS_1}$ and $g_2 = \dfrac{dA_2}{dS_2}$; $g_1 > g_2$

where the subscripts 1 and 2 denote, respectively, reservoirs 1 and 2. Assume that both reservoirs possess a linear storage-area relationship. Thus,

$$g_1 = \frac{dA_1}{dS_1} = \frac{\Delta A_1}{\Delta S_1} = \frac{A_{1f} - A_{1i}}{S_{1f} - S_{1i}}$$

and
$$g_2 = \frac{dA_2}{dS_2} = \frac{\Delta A_2}{\Delta S_2} = \frac{A_{2f} - A2_i}{S_{2f} - S_{2i}}$$

for all storage intervals S_1 and S_2, where

A_{1i} = initial area, res. 1

A_{1f} = final area, res. 1

ΔA_1 = incremental change in area, res. 1

A_{2i} = initial area, res. 2

A_{2f} = final area, res. 2

ΔA_2 = incremental change in area, res. 2

S_{1i} = initial storage, res. 1

S_{1f} = final storage, res. 1

ΔS_1 = incremental change in storage, res. 1

S_{2i} = initial storage, res. 2

S_{2f} = final storage, res. 2

ΔS_2 = incremental change in storage, res. 2.

The evaporation from each reservoir can be expressed as

$$E_1 = e_1 \left(g_1 \, (S_{1f} - S_{1i}) / 2 + A_{1i} \right)$$

$$E_2 = e_2 \left(g_2 \, (S_{2f} - S_{2i}) / 2 + A_{2i} \right)$$

where

e_1 = evaporation rate per unit area, res. 1

e_2 = evaporation rate per unit area, res. 2.

Now consider the mass balance equations of two release policies A and B:

Policy A (release R from Reservoir 1; R' from Reservoir 2)

$$S_{1f} = S_{1i} + I_2 - R - e_1 \left(g_1 (S_{1f} - S_{1i}) / 2 + A_{1i} \right) \qquad \text{(III-2a)}$$

$$S_{2f} = S_{2i} + I_2 - R' - e_2 \left(g_2 (S_{2f} - S_{2i}) / 2 + A_{2i} \right) \qquad \text{(III-2b)}$$

where $R + R' = D \; ; \quad 0 < R < D \; ; \quad 0 \lesssim R' \lesssim D.$

Policy B (release D from Reservoir 1; nothing from Reservoir 2)

$$S'_{1f} = S_{1i} + I_1 - D - e_1 \left(g_1 (S'_{1f} - S_{1i}) / 2 + A_{1i} \right) \qquad \text{(III-2c)}$$

$$S'_{2f} = S_{2i} + I_2 - e_2 \left(g_2 \, (S'_{2f} - S_{2i}) / 2 + A_{2i} \right) \qquad \text{(III-2d)}$$

Now, substituting S values where appropriate into equations III-2 and solving for the S terms there results

$$\Delta S_1 = \frac{I_1 - R - e_1 A_{1i}}{1 + e_1 g_1 / 2} \qquad \text{(III-3a)}$$

$$\Delta S_2 = \frac{I_2 - R' - e_2 A_{2i}}{1 + e_2 g_2 / 2} \qquad \text{(III-3b)}$$

$$\Delta S'_1 = \frac{I_1 - D - e_1 A_{1i}}{1 + e_1 g_1 / 2} \qquad \text{(III-3c)}$$

$$\Delta S'_2 = \frac{I_2 - e_2 A_{2i}}{1 + e_2 g_2 / 2} \; . \qquad \text{(III-3d)}$$

Now, it remains to be shown that Policy B (release entirely from the reservoir with the highest $\Delta A/\Delta S$) results in less evaporation than Policy A (any other combination of releases). In the given notation,

$$e_1\left(g_1(S'_1) + A_{1i}\right) + e_2\left(g_2(S'_2) + A_{2i}\right)$$
$$e_1\left(g_1(S_1) + A_{1i}\right) + e_2\left(g_2(S_2) + A_{2i}\right)$$

Rearranging and canceling like terms,

$$e_1 g_1 \Delta S'_1 + e_2 g_2 \Delta S'_2 < e_1 g_1 \Delta S_1 + e_2 g_2 \Delta S_2$$

or

$$e_1 g_1 (\Delta S'_1 - \Delta S_1) < e_2 g_2 (\Delta S_2 - \Delta S'_2).$$

Now, substituting equations III-3 for the S terms results in

$$e_1 g_1 \left(\frac{-D + R}{1 + e_1 g_1/2}\right) < e_2 g_2 \left(\frac{-R'}{1 + e_2 g_2/2}\right).$$

Assuming both reservoirs have equal evaporation loss rates, i.e., $e_1 = e_2$

$$g_1 \left(\frac{D - R}{1 + e_1 g_1/2}\right) > g_2 \left(\frac{R'}{1 + e_2 g_2/2}\right)$$

and

$$\frac{g_1}{1 + e_1 g_1/2} > \frac{g_2}{1 + e_2 g_2/2} \qquad \text{(III-4)}$$

since

$$D - R = R'.$$

The inequality as expressed by Equation III-4 always holds for $g_1 > g_2$. Therefore, any other selection of releases R and R' from Reservoirs 1 and 2, respectively will result in a higher evaporation loss.

<u>Exceptions to "Principle of Continuous Release"</u>

For long-term reservoir operation involving carry-over storage, it is not entirely obvious whether or not the "principle of continuous release" results in the minimum cumulative evaporation. For one thing, operating in this way during the early periods of the time span under study will no doubt minimize evaporation and likewise maximize reservoir storage contents (assuming no spill occurs). The greater amount of water in storage may result in higher evaporation losses during later portions of the operating time span. Also, markedly nonlinear storage-area curves invalidate the assumption of constant g_1 and g_2 values in the previous example, thus the inequality as expressed by equation III-4 may not always apply. Another factor which can conceivably influence the operating policy is time periods where the rainfall is in excess of the evaportion rate. During such periods reservoir surface areas should be maximized so as to maximize the net gain in water from excess rainfall.

Whether or not the "principle or continuous release" actually dictates the operating policy to minimize evaporation can best be answered by using RESEVAP to determine the optimal operating policies for selected two-reservoir systems. In the chapters which follow, reservoir systems in three regions having distinct physical and hydrologic characteristics have been modeled using RESEVAP, and the resulting operating policies were evaluated in terms of the expected type of policies to achieve minimum evaporation.

CHAPTER IV
RESERVOIR SYSTEM DATA ACQUISITION

Geographic Regions

Reservoir system charcteristics, both physical and hydrologic, as well as climatic conditions, vary greatly nationwide. Evaporation losses from reservoirs are directly affected by these varying system characteristics and climatic conditions. For this reason, the type of operating policies for evaporation reduction and the magnitude of this reduction can be expected to be different for the different geographic regions.

For this research project, two-reservoir systems possessing characteristics in each of three separate geographic locations were studied. These regions, and their pertinent hydrologic and climatic characteristics, are:

Region I
Classification: Arid
Location: Northwest Texas - Mitchell and Coke Counties
Average annual rainfall: 19.1 inches
Average annual gross evaporation: 81.9 inches
Runoff characteristics: Highly variable, occasional dry seasons. Peak runoff occurs sporadically from late spring and summer thundershowers.

Region II
Classification: Semi-arid
Location: Central California - Fresno County
Average annual rainfall: 17.1 inches
Average annual gross evaporation: 68.9 inches
Runoff characteristics: Peak runoff occurs each year from snowmelt during the late winter and early spring.

Region III
Classification: Humid
Location: Southeast Texas - Liberty and Montgomery counties
Average annual rainfall: 51.2 inches
Average annual gross evaporation: 48.0 inches
Runoff characteristics: Peak runoff may occur during winter or summer months.

See Figure IV-1 for geographic locations of the three regions.

Reservoir Inflows

In Regions II and III, two U.S.G.S. streamgaging stations were selected from which the runoff records were used to represent inflow into the two reservoirs. In each region, 10 successive years of runoff data were selected which contained representative minimum and maximum flows for the available data at each station. The average magnitude of runoff values at each of the streamgaging stations was of approximately the same size. The selected streamgaging stations and their corresponding periods of recorded runoff used are shown on Table IV-1.

It is likely that longer historical inflow sequences will show differences in the magnitude and distribution of inflows. However, it is felt that the selected

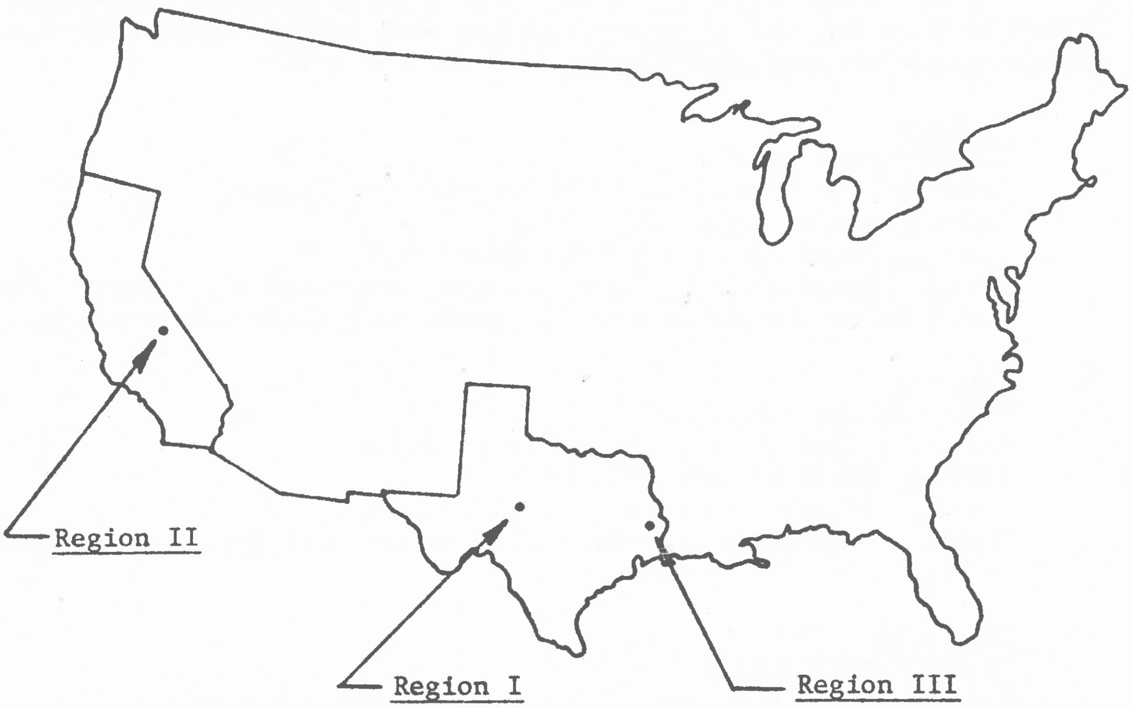

Figure IV-1

Geographic Locations, Regions I, II and III

Table IV-1

Streamgaging Stations, Regions II and III

Location	U.S.G.S. Streamgaging Station	Selected Period of Inflow (water years)	Drainage Area (sq. miles)	Avg. Yearly Inflow (cfs-days)
Region II	11257500 Fresno River near Knowles, Ca. (inflow to Res. 1)	1958-1967	133	2353.4
	11258000 Fresno River near Doulton, Ca. (inflow to Res. 2)	1958-1967	258	3207.7
Region III	8071000 Peach Creek at Splendora, Tx. (inflow to Res. 1)	1961-1970	117	1594.5
	807000 East Fork San Jacinto River near Cleveland, Tx. (inflow to Res. 2)	1961-1970	325	5209.2

10-year records were of sufficient length to show the relative importance of evaporation reduction with respect to other reservoir system operating criteria.

The streamgaging stations in Region I contained either an inadequate number of successive years of recorded runoff or periods of substantial upstream regulation. For these reasons, the U.S. Army Corps of Engineers computer program HEC-4 was used to reconstitute missing data from available records of six streamgaging stations to represent inflow to Reservoirs 1 and 2. These two sets of reconstituted runoff data represent inflows at two hypothetical reservoir locations on the Upper Colorado River. The ratios of the drainage areas of the reservoirs to the drainage areas of the streamgaging stations were used as factors in adjusting the reconstituted flow data to represent inflows at the reservoir sites. Tables IV-2a and IV-2b show respectively, the streamgaging stations used for reconstitution and for reservoir inflows.

For the sake of uniformity in comparisions of the studies made in each of the three regions, the inflows for Reservoir 1 and Reservoir 2 were each multiplied by a coefficient such that the mean inflow over the 10 year period is the same for each region. That is, for all three regions, the mean inflow to Reservoir 1 is the same, and the mean inflow to Reservoir 2 is the same. Consequently, the total quantity of inflow to each reservoir is also the same. Table IV-3 shows the inflow adjustments for each region, and Table IV-4 shows the resulting inflows after adjustment by the coefficients.

It is recognized that the adjustment of the inflows by three coefficients changes the statistical properties of the inflow sequences; however, the adjustments were deemed to be small enough so that the inherent charcteristics of the inflows in each region were preserved. Refer to Displays 1 through 3, Appendix D for plots of the time sequence of inflows to each reservoir for each region.

Evaporation Rates

Gross evaporation rates for Regions I and III, both of which are in Texas, were taken from the appropriate evaporation tables in Report No. 64, Texas Water Development Board. Monthly average values were used based on the years 1940-1965, inclusive. For Region II, Class A pan evaporation data at Pine Flat Dam (nearest evaporation station to the streamgaging stations) was obtained from Bulletin 73-79, California Department of Water Resources. Monthly average values were based on the period 1950-1976. Pan-to-lang evaporation coefficients were taken from the Reservoir Regulation Manual for Pine Flat Reservoir, U.S. Army Corps of Engineers. The pan evaporation data were then converted to lake surface values using these coefficients.

Average monthly rainfall values were subtracted from the gross evaporation rates to determine the actual monthly evaporation rates. The monthly rainfall values were obtained from "Climates of the States"; Vol. 2, National Oceanic and Atmospheric Administration. These average rainfall values are based on the period 1931-1960. The locations from which the monthly rainfall values were taken are as follows:

Region I: Average of values at Snyder and San Angelo, Tx.
Region II: Piedra, Ca.
Region III: Liberty, Tx.

The resulting net evaporation rates are shown on Table IV-5. Negative evaporation rates represent months where the rainfall exceeded the evaporation

Table VI-2a
Streamgaging Stations Used for HEC-4 Reconstitution of Flow Data, Region I

U.S.G.S. Number	Name	Drainage Area (sq. mi.)	Period of Record
8119000	Bluff Creek nr. Ira Tx	42.6	1948 - 1965
8120500	Deep Creek nr. Dunn, Tx	188	1953 - 1977
8121500	Morgan Creek nr. Westbrook, Tx.	288	1954 - 1963
8122000	Graze Creek nr. Westbrook, Tx	21.2	1954 - 1959
8123500	Champlin Creek nr. Colorado City, Tx	158	1948 - 1959
8123800	Beals Creek nr. Westbrook, Tx.	973	1959 - 1977

TABLE IV-2b
Factors for Computing Inflows, Region I

	Streamgaging Stations Used	Selected Drainage Area, Reservoir (sq. miles)	Total Drainage Area, Gaging Stations (sq. miles)	Adjustment Factor
Reservoir 1	8119000 8120500 8121500	940	460	2.04
Reservoir 2	8119000 8120500 8123800	4100	1200	3.42

Table IV-3

Inflow Adjustment Coefficients

		Mean Inflow, 10-yr. period (cfs-days)	Adjustment Coefficient
Region I	Reservoir 1	1735.2	1.356
	Reservoir 2	3847.2	1.000
Region II	Reservoir 1	2353.4	1.000
	Reservoir 2	3207.7	1.199
Region III	Reservoir 1	1594.5	1.476
	Reservoir 2	5209.2	.739

Table IV-4

Regional Inflow Characteristics (cfs-days)

		Region I	Region II	Region III
Reservoir 1	avg. inflow	2,352.5	2,353.2	2,353.0
	min. inflow	0	0	250.0
	max. inflow	48,514.0	20,023.0	18,563.0
	std. deviation	6,928.6	3,324.0	3,236.3
Reservoir 2	avg. inflow	3,847.2	3,845.6	3,849.1
	min. inflow	0	0	167.0
	max. inflow	48,556.0	44,759.0	32,261.0
	std. deviation	8,131.1	6,964.0	5,931.5

Table IV-5
Monthly Evaporation Rates (in./unit area)

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Region I	5.02	4.00	2.43	2.12	2.32	4.02	4.48	4.08	7.28	8.68	9.54	6.59
Region II	3.99	.70	-2.16	-2.39	-2.01	-.46	1.87	4.84	7.15	9.30	9.05	7.07
Region III	1.26	-.45	-2.38	-2.55	-2.11	-.38	-1.18	-.36	.92	.53	2.14	1.43

Table IV-6
Monthly Demand Sequence (ac-ft)

OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
5,000	5,000	5,000	5,000	5,000	5,000	10,000	13,000	16,000	13,000	13,000	13,000

rate. In actuality annual climatic changes cause the evaporation rates to differ each year. It is assumed that the differing evaporation rates from year to year are of minor importance with respect to other reservoir system descriptive data.

Monthly Demands

A hypothetical monthly demand sequence was selected to represent a typical constant municipal or industrial demand coupled with a seasonal agricultural demand. Table IV-6 shows the monthly demand sequence.

As discussed in Chapter II, the total monthly release for the System I configuration is restricted to the monthly demand. For System II, however, a further restriction is placed on Reservoir 1, via the parameter RD1 (IT), such that the release from this reservoir may never exceed 18,000 acre-feet per month.

With the smallest monthly demand being 5000 acre-feet, a selection of 2000 acre-feet as the state space discretization increment for Reservoir 1 was used. From 0 to 2000 acre-feet, the discretization values were 0, 500, 1000 and 2000 acre-feet, in order that better accuracy would be achieved for operating policies in which Reservoir 1 was at low storage levels.

Storage-Area Curves

The storage-area curve for Reservoir 1 was chosen to be linear, while for Reservoir 2 the actual storage-area curve at Pine Flat Reservoir in California was used. Pine Flat Reservoir is situated in a relatively deep canyon as compared to the linear shape as defined for Reservoir 1, which represents much flatter terrain. Figures IV-2 and IV-3 show, respectively, the storage-area curves and the corresponding $\Delta A/\Delta S$ curves for each reservoir. These same curves were used in each of the three regions.

Initial Storages

As explained in later Chapters, proper calibration of the model was best achieved when the initial storages for Reservoirs 1 and 2 were 28,000 acre-feet and 55,000 acre-feet, respectively. These initial storages are in approximately the same proportion as are the mean inflows for Reservoirs 1 and 2-that is, the initial storage and mean inflow to Reservoir 1 are approximately 60 %of the corresponding values for Reservoir 2.

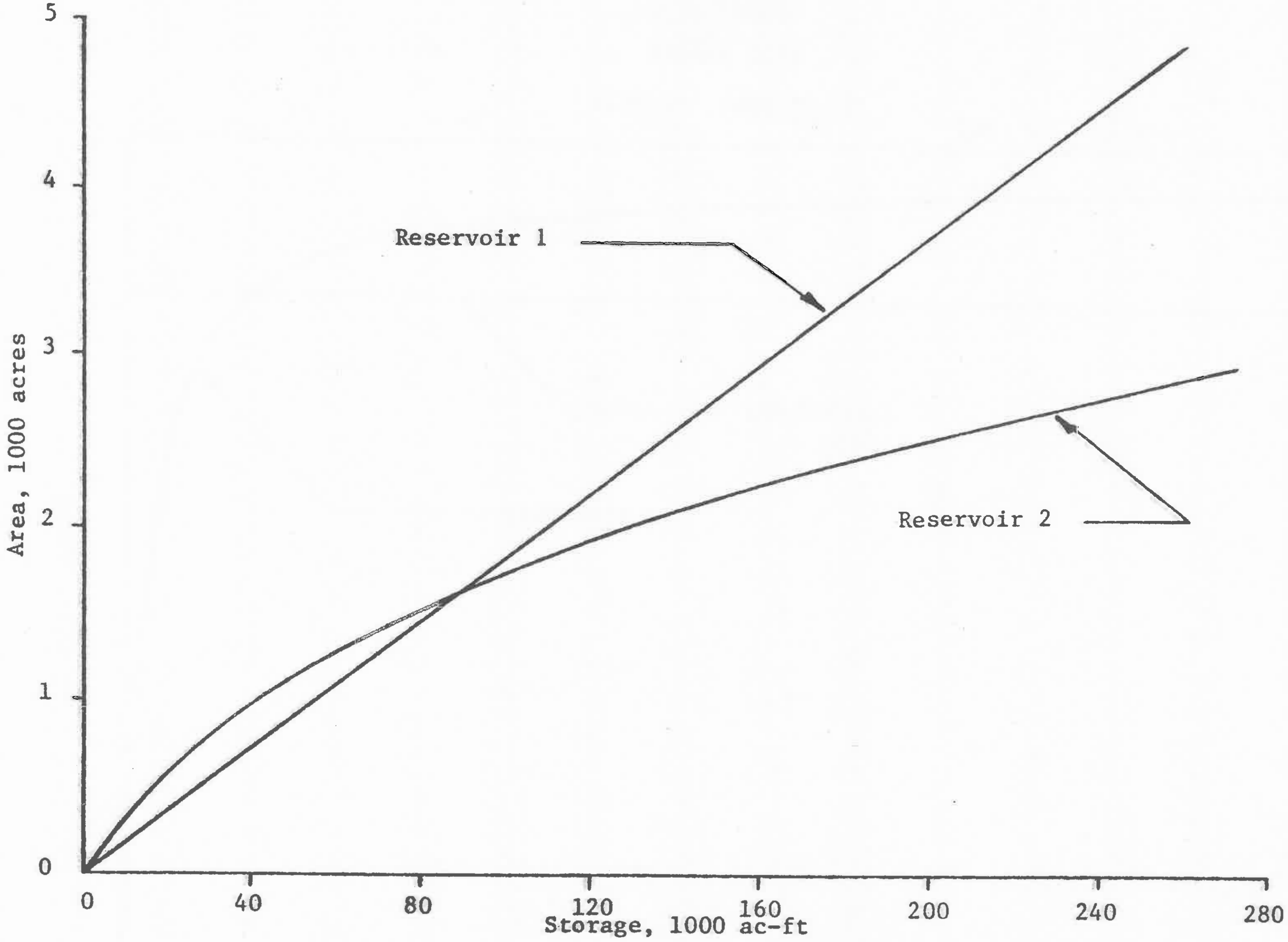

Figure IV-2

Storage-Area Curves

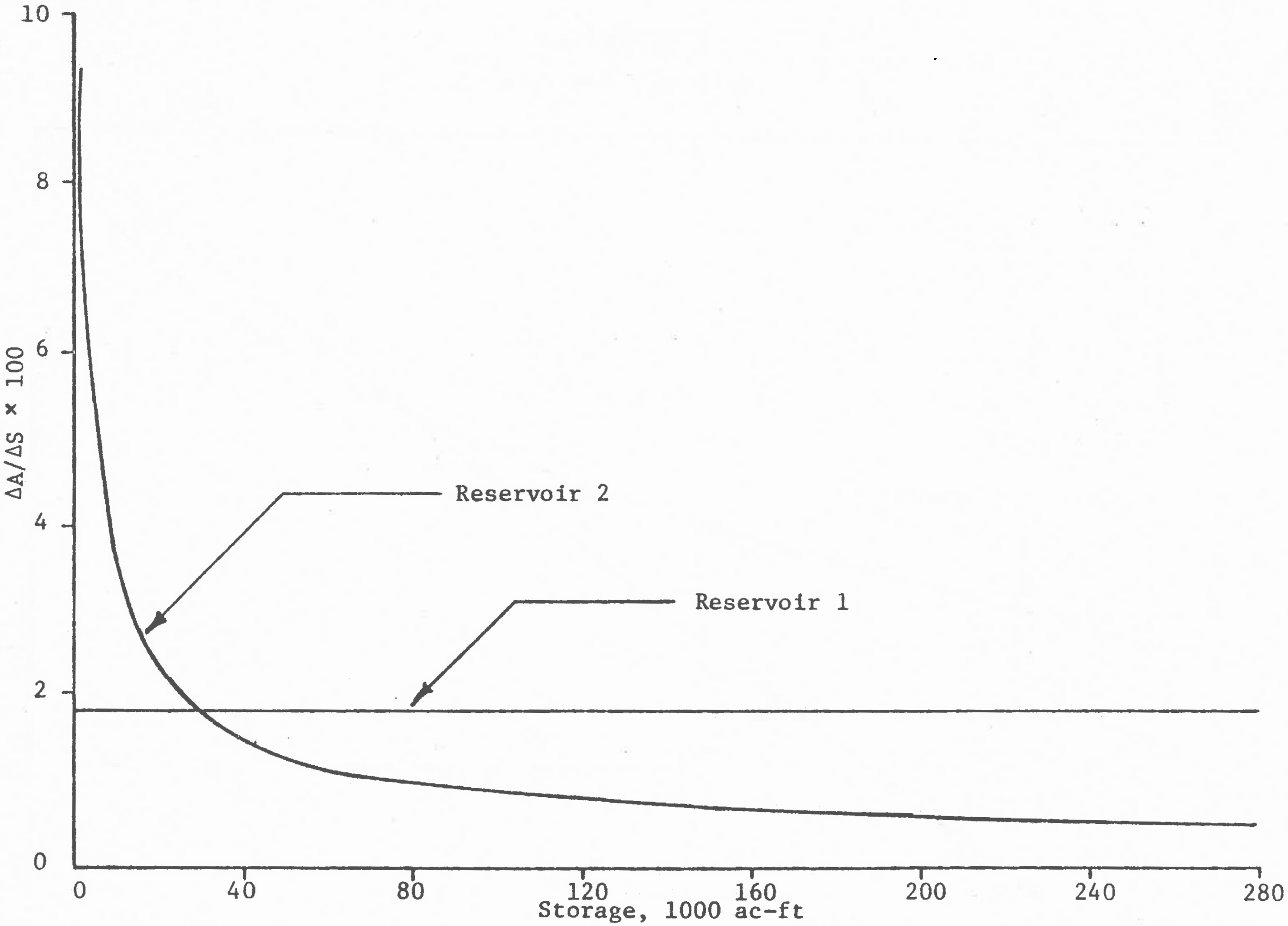

Figure IV-3

ΔA/ΔS Curves

CHAPTER V
EVAPORATION MINIMIZATION

Study Features

The purpose of these studies, which are catagorized as Test D1, is to quantify evaporation losses in each of the three regions under investigation. Also, Test D1 will distinguish between the optimal operating policies, with respect to minimizing evaporation, for each of the three regions.

As outlined in Chapter IV, the reservoir system as modeled in each region is identical, the only differences being those which are distinctive of each region, i.e., the monthly evaporation loss, and the variance and seasonal distribution of monthly inflows. Only Objective 1 (minimize cumulative evaporation) is utilized for Test D1. For Objective 1, reservoir spill will occur so long as it serves the objective of minimizing evaporation. The important feature of Test D1 is that the maximum storage in each reservoir is large enough so that no spill ever occurs during the 10-year period. Thus, considering the mass balance equation for the entire 10-year period, the only difference among the three regions is the evaporation loss. For each region, both System I and System II test runs were made. Table V-1 shows the results of these six test runs.

Region I

Region I is clearly the least favorable region as far as the quantity of evaporation loss is concerned. Of the total volume of water required over the 10-year period of 1,080,000 acre-feet, over 10% is lost to evaporation. Displays 1 & 2, Appendix E show the tabulation and plot of the month-by-month operation policy for System I. The "principle of continuous release," as explained in Chapter III, seems to be followed in Region I. Refering to Figure IV-3, it is seen that the initial value of $\Delta A/\Delta S$ for Reservoir 1 is higher than that of Reservoir 2. Therefore, Reservoir 1 should be released from first, as is borne out by the results. Large releases continue to be made from Reservoir 1 until it is empty.

The fact that the release from Reservoir 1 is not the entire demand quantity for these initial months is because of the approximations introduced by the state space discretization increment. For each of these months, a decrease in storage in Reservoir 1 by the increment of 2000 acre-feet will push the quantity released up to a value greater than the demand, in which case the policy is infeasible. Once Reservoir 1 becomes empty, the evaporation loss in that reservoir reduces to zero and the reservoir is kept empty by releasing the entire monthly inflow. Occasional large inflows which exceed the monthly demand cause Reservoir 1 to deviate from zero storage.

The System II run for Region I shows somewhat better results. Since it is optimal to keep Reservoir 1 empty as shown by the System I run, this is better accomplished in System II, where Reservoir 1 can make releases in excess of the demand, thereby enabling Reservoir 1 to remain at zero storage more frequently. This is evident by comparing the average storages in each Reservoir for Systems I and II in Table V-1. For System II, Reservoir 1 has a lower average storage and Reservoir 2 has a correspondingly higher average storage, as compared to System I.

Region II

Results of the test runs for Region II show evaporation losses at just over 7% of the total demand. Once again, the "principle of continuous release" governs the operation policy, both for the System I and System II test runs. Refering to Displays 3 and 4, Appendix E, it is noted that deviation from the continuous release policy occurs during months with negative evaporation rates. During these months the net gain in water from excess rainfall is maximized by releasing from Reservoir 2 and letting Reservoir 1 fill since, in this way, the total reservoir surface area is maximized. As with other test runs, the approximations introduced by the state space increment dictate that Reservoir 2 cannot release all of the demand during these months, as this would render the policy infeasible.

Region III

The test runs for Region III presented results distinctly different from those of Regions I and II, and expectedly so since the majority of the monthly evaporation rates are negative. The "principle of continuous release" dominates, but in the reverse sense in that the reservoir with the lowest value of $\Delta A/\Delta S$ is released from first, which is Reservoir 2. See Displays 5 and 6, Appendix E, for the results of the System II test run. Note the monthly intervals March, 1970 to July, 1970 and February, 1971 to September, 1971. These months show deviation from the continuous release policy, the reason for which may be the combined effect of many factors difficult to identify. A plausible explanation could be the following: During the first eight years of the study, no deviation from the continuous release policy is observed (within the limits of the state space discretization), except for August, 1968 to November, 1968, where Reservior 2 is nearly empty. Throughout the first eight years, Reservoir 1 gradually fills, since it is releasing as little water as possible. It may be that, by March, 1970 it becomes so full that its subsequent evaporation loss is exceedingly high, more than offsetting the net gain in water during the negative evaporation rate months. Thus, it becomes optimal to make large releases from Reservoir 1, thereby reducing the evaporation losses. Table V-1 shows that the overall effect of the objective of minimizing evaporation is to maximize the gain in water, since the total evaporation is negative. This gain of water is about 1.7% of the total demand for the 10-year period.

Regional Comparisons

Of the three regions studied, Region III is undoubtedly the best location with respect to evaporation losses, because of its negative monthly evaporation rates. Region II is next, with Region I experiencing the greatest losses because of its larger monthly evaporation rates. However, the inflow characteristics also play a part in determining the effectiveness of the optimal operating policy. The average of the monthly evaporation rates for regions I, II and III are 5.05, 3.08 and -.26 inches per unit area respectively. The ratio of the average evaportion rate to the total evaporation loss is shown in Table V-2 for each region. The significance of this ratio is that it measures, to some degree, the relative efficiency of the regions in achieving minimal evaporation losses, with respect to the inflow distribution. For example, Region II is not as efficient as Region I since, given the decrease in the average evaporation rate of 39%, the decrease in evaporation loss is only about 32%, thus Region II has a lower ratio than Region I. Also, because of its greater flexibility, System II is slightly more efficient than System I for each region. The values for Region III are infinity since Region III

Table V-1

Test D1

(all values in ac-ft)

		Region I	Region II	Region III
System I	total evap.	118,009	80,747	-17,784
	avg. storage, Res. 1	13,017	11,467	300,750
	avg. storage, Res. 2	151,580	161,646	126,239
	total evap. as % total demand	10.9%	7.5%	1.6%
System II	total evap.	114,171	76,260	-18,110
	avg. storage, Res. 1	5,346	3,700	295,667
	avg. storage, Res. 2	160,827	171,303	131,358
	total evap. as % total demand	10.6%	7.1%	1.7%

Table V-2

Ratio of Avg. Evap. Rate to Total Evap. Loss

Test D1

	Region I	Region II	Region III
System I	$4.28\ 10^{-5}$	$3.81\ 10^{-5}$	∞
System II	$4.42\ 10^{-5}$	$4.04\ 10^{-5}$	∞

experienced no total losses from evaporation, but rather, gains in water from rainfall.

Table IV-4 shows the standard deviation from the mean inflow for each of the regions. The standard deviations for Region I are higher than for Region II. This might suggest that the greater inflow fluctuations as indicated by the larger standard deviation result in greater evaporation reduction efficiency. Although Region III has a standard deviation which is lower than Region II, its efficiency ratio is larger because of the zero evaporation losses. The relationship of the standard deviation of the inflows to the operating policy results will be further discussed in Chapter VII.

CHAPTER VI
WATER CONSERVATION

Study Features

The underlying objective of this research project is water conservation. Hence, evaporation reduction policies must also be evaluated in relation to their effects on other types of water conservation measures. In the context of this research, the reduction of reservoir system spill is the other type of water conservation measure which must be considered. The distinguishing feature of the test runs described in this chapter is that the maximum allowable storage in Reservoirs 1 and 2 is limited such that a certain amount of system spill occurs during the 10-year study period. Each of the three objectives (minimize evaporation, minimize spill or minimize the sum of evaporation plus spill) is applied to all three regions.

Two sets of test runs were conducted in this chapter. The first set, labeled collectively as Test A1, employs the fixed demand sequence described in Chapter IV. Test A1 used the comparisons of the quantities of total water loss for the 10-year study period as an indication of the degree of water conservation achieved for each of the Objectives 1, 2 or 3. The second set of test runs, labeled Test H1, used a modified version of RESEVAP which determined, by iteration, the largest percent increase in the fixed demand sequence used in Test A1 such that no shortage occurred over the 10-year period. This increase in reservoir system yield is the long-term objective of water conservation in reservoir systems, that is, to conserve water for reservoir system firm yield increases.

Required Conservation Storage

It is immediately apparent that the differing inflow characteristics of each region will have an influence on the quantity and occurence of spill in each region. Thus, for fixed values of maximum reservoir storage for all three regions, the resulting system spill will not be comparable among the regions. The procedure by which the test runs for each region are made comparable is to limit the storage in Reservoirs 1 and 2 to those values which result in both reservoirs becoming nearly empty just once during the 10 years. This volume of storage is then the minimum conservation storage required to supply the monthly demand. Since it was anticipated that Objective 1 would result in the greatest water loss and thus require the largest conservation storage, the Objective 1 test runs were used to calibrate the model for each region. Table VI-1 shows the required conservation storage for each region. Region II, because of its relatively smaller values of inflow magnitude, requires the largest conservation storage. Region III requires the least, primarily because of its negative monthly evaporation rates.

Table VI-1

Maximum Allowable Storages (ac-ft)

	Region I	Region II	Region III
Reservoir 1	80,000	124,000	60,000
Reservoir 2	125,000	195,000	94,000

These test runs, labeled as Test A1, do not consider any flood control space in any of the regions which, in actual practice, may be provided for. Test A1 simply shows the volume of spill that occurs as a result of limiting the reservoir sizes to those required to supply the monthly demand for the 10-year study period.

Total Water Loss, Objectives 1 and 2

The results of the test runs for Objectives 1 and 2 are summarized in Tables VI-2a and VI-2b, respectively. Consistent with the results obtained in Test D1, the total water loss is the higher for Region I and lower for Region II. However, the quantities of spill for Region III greatly exceed those of Regions I and II. Because of its negative monthly evaporation rates, Region III requires less conservation storage than do Regions I and II, and this in turn causes the reservoir system spill to be relatively large.

In regard to total water conservation, Objective 2 (minimize cumulative spill) results in the least amount of total water loss. Comparing Objective 2 to Objective 1, total water loss in Region I is reduced by about 8% for System I and 13% for System II. For Region II the reduction is 25% for System I and 36% for System II. Comparing Objectives 1 and 2 for Region III it is seen that virtually no reduction is achieved in total water loss by minimizing spill instead of evaporation.

Objective 1

The Objective 1 test run for Region I follows the "principle of continuous release," similar to the policy in Test D1. For Region II, however, the first 42 months (through March, 1962) show that Reservoir 2 is releasing most of the water while Reservoir 1 is allowed to gradually fill. Then the trend reverses, and Reservoir 1 begins to supply the monthly demand and becomes empty in January, 1963. From here on the policy is similar to that of Test D1. See Appendix F, Displays 1 and 2 for the tabular and graphical results of the Region II test run. Apparently restraining the maximum storage in the reservoirs causes the operaing policy to deviate from the continuous release policy during the first 42 months. Note the larger releases from Reservoir 1 during the interval February, 1959 to April, 1959. These large releases enable Reservoir 2 to spill excess water during this period which could have contributed towards the demand quantity. In effect the operating policy has forced a spill from the system to reduce the reservoir storage levels and thereby reduce evaporation.

The Objective 1 test run for Region III is similar to that of Test D1 in that the negative evaporation rates cause numerous reversals in the release policy. Some months Reservoir 1 releases most of the water while in other months Reservoir 2 makes the major releases.

Table VI-2a

Test A1, Objective 1 (minimize evaporation)

(all values in ac-ft)

		Region I	Region II	Region III
System I	total evap.	92,702	73,846	-5,779
	total spill	230,963	178,632	420,263
	total loss	323,664	252,479	414,484
	avg. storage, Res. 1	12,533	20,642	47,033
	avg. storage, Res. 2	86,579	118,994	55,901
System II	total evap.	86,431	72,574	-6,035
	total spill	253,233	266,776	419,888
	total loss	339,664	299,350	413,853
	avg. storage, Res. 1	10,471	29,454	46,817
	avg. storage, Res. 2	79,788	107,342	54,321

Table VI-2b

Test A1, Objective 2 (minimize spill)

(all values in ac-ft)

		Region I	Region II	Region III
System I	total evap.	113,062	87,277	-5,385
	total spill	183,570	103,051	419,277
	total loss	296,632	190,329	413,892
	avg. storage, Res. 1	35,958	33,983	44,433
	avg. storage, Res. 2	82,611	132,108	58,615
System II	total evap.	113,332	86,752	-5,117
	total spill	183,287	103,569	418,971
	total loss	296,619	190,322	413,853
	avg. storage, Res. 1	36,708	32,879	45,183
	avg. storage, Res. 2	81,914	133,509	56,893

Objective 2

In general, the Objective 2 test runs for each region attempt to keep both reservors as full as possible without spilling. During prolonged periods of no spill, however, the additional objective of minimizing evaporation determines the policy. Thus, during these periods, the operation policies resemble those of the Objective 1 test runs. See Displays 3 and 4, Appendix F for the tabular and graphical results of the Objective 2 test run for Region I, System II. Note that in the months of April and May, 1967 Reservoir 2 is full and spilling, while Reservoir 1 is not yet full. At the end of June, 1966 both reservoirs are full and Reservoir 2 is spilling. Between June, 1966 and April, 1967 the operating policy tries to draw down Reservoir 2 as fast as possible (again, within the limits of the state space discretization) by allowing Reservoir 2 to supply most of the required demand. In April, 1967 Reservoir 2 is subjected to an extremely high inflow and is forced to spill even though Reservoir 1 has available storage space.

Referring again to Table VI-2b, it is noted that, for Region II, System I results in less spill than System II (103, 051 acre-feet vs. 103, 569 acre-feet). For either Objectives 1 or 2, it is normally expected that System II will achieve the objective with results at least as good as System I, since two reservoirs in series can exactly duplicate any operating policy followed by reservoirs in parallel. Due to the additional objective of minimizing evaporation in situations of equal cumulative spill, however, transfers of water from Reservoir 1 to Reservoir 2 take place in the System II test run which minimize evaporation during prolonged periods of no spill. These transfers of water, which cannot occur in System I, force System II to spill more water than System I in the long run.

Objective 3

As discussed in Chapter IV, RESEVAP has the capability of also minimizing the cumulative sum of evaporation plus spill, referred to as Objective 3. This objective is expected to produce the absolute minimum total water loss, within the limitations of the model. Table VI-3 summarized the results of the Objective 3 test runs for each of the regions.

The unexpected result of these test runs is that Objective 3 produces exactly the same total water loss as does Objective 2 for each region. It is evident, then, that minimizing the total sum is no better than minimizing the spill alone. Upon further consideration, this is logical when the results are analyzed in the following way: Consider the Objective 2 test run, where the cumulative spill has been minimized. Now, if the total water loss from Objective 2 is going to be improved upon by Objective 3, there are presumably months where the evaporation can be reduced without causing an increase in the system spill. Yet, this cannot happen because of the release being constrained to the monthly demand. Any water prevented from evaporating must necessarily spill, since the storage levels in the reservoirs must increase by that amount. From another perspective, consider the fact that if Objective 2 were to be any worse than Objective 3, it must be that the decrease in cumulative spill realized by Objective 2 is less than the corresponding increase in cumulative evaporation, when compared with Objective 3. This is an impossibility since no more than that additional quantity of water prevented from spilling can possibly be lost to evaporation. Thus it is seen that when comparing Objectives 2 and 3, the difference in cumulative spill is exactly compensated for by an equal and opposite difference in cumulative evaporation.

Table VI-3

Test A1, Objective 3 (minimize evaporation + spill)

(all values in ac-ft)

		Region I	Region II	Region III
System I	total evap.	108,245	83,981	-5,466
	total spill	188,387	106,348	419,358
	total loss	296,632	190,329	413,892
	avg. storage, Res. 1	26,558	23,367	44,800
	avg. storage, Res. 2	90,160	142,830	58,503
System II	total evap.	107,827	83,409	-5,591
	total spill	188,792	106,913	419,444
	total loss	296,619	190,322	413,853
	avg. storage, Res. 1	24,325	22,313	44,283
	avg. storage, Res. 2	93,520	144,202	57,133

Basic Operating Policy

In order to determine the amount of improvement that could be made in reducing evaporation or total water loss in each region, some basic type of operation policy must be established in each region to which the optimal policies as determined by RESEVAP can be compared. To determine a basic operating policy, the U.S. Army Corps of Engineers computer program HEC-3, "Reservoir System Analysis," is used to model each region with the identical reservoir system data for each of the three regions. These test runs are hereinafter labeled as Test C1.

HEC-3 is a detailed reservoir system simulation program designed for accurate simulation of actual reservoir systems. The program is flexible enough so that the two-reservoir system as modeled by RESEVAP can be exactly duplicated by HEC-3. The method of evaporation calculation used in HEC-3 is identical to that of RESEVAP.

The operating policy guidelines in HEC-3 are specified using the "level balancing technique", whereby the total storage in each reservoir in the system is divided into a maximum of eight separate levels. The releases from the reservoir system are made in such a way as to attempt to keep all the reservoirs at the same storage level. Commonly, a basic level arrangement against which others can be compared is to set up the levels so that each one represents the same fraction of total storage for each reservoir. This is the type of level arrangement used for the two-reservoir system as modeled in this study. Any release to be made from the reservoir system is regulated such that each reservoir will be at the same level, i.e., the storage level which represents the same fraction of the total reservoir storage, after the release.

Displays 1 through 3, Appendix G show the plots of the System I operation policies for each region, as determined by HEC-3. These plots show that the storages in each reservoir flucuate such that each reservoir is kept at the same percent of total storage, within the limits of the inflow variability.

Table VI-4 summarizes the results for Test C1. Considering evaporation alone, the amount of reduction achievable in each region can be evaluated by comparing the results in Table VI-2a with Table VI-4. These reductions in evaporation realized by the Objective 1 test runs are shown in Table VI-5. It can be concluded from Table VI-5 that considerable reduction in evaporation can be achieved in Regions I and II albeit at the expense of increasing reservoir system spill.

The most significant result of the comparison of Test A1 with Test C1 is that for each region and for each reservoir system configuation, the total water loss for the 10-year period is virtually the same (Test C1 is never higher than .3% of Test A1). The exception is Test A1, Objective 1, where the minimization of evaporation results in system spill quantities which greatly increase the total water loss. Apparently the policy guidelines followed in Test C1 were just as good with respect to the total water loss as the Test A1, Objective 3 (or Objective 2) test runs, where the total water loss is minimized.

Optimal Operating Policies

The results of Objectives 2 and 3, Test A1 and Test C1 indicate that there exists a certain range of operating policies which are optimal since they minimize the total water loss. This range is coined the "compensation range," in that for any two operating policies within this range, the difference in total evaporation is exactly compensated for by the difference in total spill, rendering the two

Table VI-4

TEST C1

(all values in ac-ft)

		Region I	Region II	Region III
System I	total evap.	115,530	96,280	-5,200
	total spill	181,188	94,212	419,208
	total loss	296,718	190,492	414,008
	avg. storage, Res. 1	44,827	63,145	40,293
	avg. storage, Res. 2	72,982	97,651	63,671
System II	total evap.	115,550	96,340	-5,200
	total spill	181,176	96,596	419,208
	total loss	296,726	190,936	414,008
	avg. storage, Res. 1	44,781	61,820	40,277
	avg. storage, Res. 2	73,085	99,729	63,687

Table VI-5

Evaporation Reduction, Test A1 compared to Test C1

(values in ac-ft)

		Region I	Region II	Region III
System I	evaporation reduction	22,828	22,434	579
System II	evaporation reduction	29,119	23,766	835

policies equivalent with respect to the total water loss. In more definitive terms, any two operating policies A and B within the "compensation range" will satisfy equation VI-1 to follow:

Let

e_i = evaporation rate for both reservoirs during month i, i=1, N.

$\overline{S1}_{Ai}$ = avg. storage in Res. 1 for policy A, month i.

$\overline{S2}_{Ai}$ = avg. storage in Res. 2 for policy A, month i.

$\overline{S1}_{Bi}$ = avg. storage in Res. 1 for policy B, month i.

$\overline{S2}_{Bi}$ = avg. storage in Res. 2 for policy B, month i.

$f_1(S)$ = surface area, Res. 1 expressed as a function of storage.

$f_2(S)$ = surface area, Res. 2 expressed as a function of storage.

$$\Delta E = \sum_{i=1}^{N} e_i f_1(\overline{S1}_{Ai}) + \sum_{i=1}^{N} e_i f_2(\overline{S2}_{Ai}) \qquad \text{(VI-1)}$$

$$- \sum_{i=1}^{N} e_i f_1(\overline{S1}_{Bi}) + \sum_{i=1}^{N} e_i f_2(\overline{S2}_{Bi}) = -\Delta SP$$

where

ΔE = total evap., policy A - total evap., policy B

ΔSP = total spill, policy A - total spill, policy B.

For simplicity's sake, consider an approximation of equation VI-1 as follows:

$$\Delta E = N \bar{e} f(\bar{S}) = -\Delta SP \qquad \text{(VI-2)}$$

where

N = total number of months

$\bar{e}$ = average of the monthly evaporation rates e_i, i=1, N

$\bar{S}$ = average reservoir system storage over the total N months f = composite storage-area function, assuming both reservoirs at the same site.

If, in Policy B, the spill (ΔSP) is increased, it can be expected that the average reservoir system storage, $\bar{S}$, will correspondingly decrease due to the absence of the water thus spilled. Due to decreased storage levels, the exposed surface area, and thus the evaporation, will likewise decrease. For a given quantity of ΔSP increase, Policy B will remain in the "compensation range" provided that the decrease in $\bar{S}$ is sufficiently large or N is large enough such that equation VI-2 holds. However, if SP is too large, ΔE $- \Delta SP$ and policy B is no longer in the "compensation range," becoming sub-optimal. This is the situation for the Objective 1 test runs, Test A1.

Limitations of Objective 2

The test runs for Objective 2, Test A1 produce the operating policies for minimum spill. The quantities of spill in these test runs are actually larger than for those of Test C1, which are based on the operating policies as specified by the storage level arrangement in HEC-3. The fundamental reason for this is that the DP algorithm written for RESEVAP cannot really optimize the value of the objective function at stages where it takes on zero values for every state. Hence the inclusion of an additional objective, as discussed in Chapter II, by which a sub-optimal path selection can be made. This additional objective (minimize cumulative evaporation for equal cumulative spill policies) actually works against the objective of minimizing spill. This is most apparent in the test runs for Regions I and II, where the "principle of continuous release" for minimum evaporation dictates that Reservoir 1 should remain empty, while for minimum spill both reservoirs should be kept as full as possible.

Reservoir System Firm Yield

Water conservation measures in reservoir systems are generally practiced for the purpose of increasing the firm yield of the system, i.e., the maximum quantity of water which can be guaranteed during a critical dry period. The test runs of Test H1 begin with both reservoirs at full storage and show the percent increase in the demand sequence used in Test A1 such that both reservoirs become nearly empty once during the 10-year period. Thus the firm yield obtainable for each of the three objectives is determined, for the selected 10-year period of inflows.

Tables VI-6a, VI-6b and VI-6c summarize the results of Test H1 for Objectives 1, 2 and 3 respectively.

It is noted that for Regions I and II, substantial increases in reservoir system yield are realized with Objectives 2 and 3 as compared to Objective 1. In addition to the firm yield increases, Objectives 2 and 3 showed smaller total losses and greater total ending storages.

The greater total ending storages for Objectives 2 and 3 show a conservation of water in addition to the increases in firm yield achieved for these two objectives. This additional water is available for temporary increases in yield at some future time or may be considered as surplus storage to offset any future, more severe, critical dry period.

Table VI-6a

Test H1, Objective 1 (minimize evaporation)

(all values in ac-ft)

		Region I	Region II	Region III
System I	total evap.	100,524	72,127	-5,706
	total spill	257,586	326,553	490,278
	total loss	358,110	398,680	484,573
	avg. storage, Res. 1	15,938	22,913	47,400
	avg. storage, Res. 2	99,144	123,733	56,284
	% yield increase	8.8	8.9	.1
	total ending storage	147,000	219,775	64,614
System II	total evap	91,268	73,256	-5,961
	total spill	189,332	362,821	489,919
	total loss	280,600	436,077	483,958
	avg. storage, Res. 1	20,304	43,371	47,167
	avg. storage, Res. 2	77,829	97,996	54,715
	% yield increase	18.1	10.2	.1
	total ending storage	125,000	168,562	65,229

Table VI-6b

Test H1, Objective 2 (minimize spill)

(all values in ac-ft)

		Region I	Region II	Region III
System I	total evap.	120,181	74,347	-5,262
	total spill	89,334	187,642	487,914
	total loss	209,515	261,989	482,653
	avg. storage, Res. 1	37,583	29,142	44,517
	avg. storage, Res. 2	96,081	112,408	59,125
	% yield increase	20.1	16.9	.2
	total ending storage	174,094	269,983	64,952
System II	total evap.	122,538	74,065	-5,224
	total spill	86,062	187,272	487,391
	total loss	208,600	261,337	482,166
	avg. storage, Res. 1	43,667	25,229	46,000
	avg. storage, Res. 2	89,623	114,796	57,112
	% yield increase	20.2	16.9	.3
	total ending storage	174,060	270,635	64,911

Table VI-6c

Test H1, Objective 3 (minimize evaporation + spill)

(all values in ac-ft)

		Region I	Region II	Region III
System I	total evap.	118,465	74,308	-5,374
	total spill	90,793	187,681	488,026
	total loss	209,258	261,989	482,653
	avg. storage, Res. 1	33,367	29,308	45,233
	avg. storage, Res. 2	100,373	112,327	58,588
	% yield increase	20.1	16.9	.2
	total ending storage	174,352	269,983	64,952
System II	total evap.	119,170	13,701	-5,683
	total spill	89,173	187,585	487,850
	total loss	208,343	261,286	482,166
	avg. storage, Res. 1	35,317	26,313	47,350
	avg. storage, Res. 2	98,226	114,920	56,156
	% yield increase	20.2	16.9	.3
	total ending storage	174,318	270,686	64,911

CHAPTER VII
RESERVOIR SYSTEM CHARACTERISTICS AND THEIR IMPACT ON WATER CONSERVATION

Study Features

In the studies described in this chapter, the influence of certain physical and hydrologic reservoir system characteristics on the optimal operating policies and on the magnitudes of the water loss components (spill and evaporation) were investigated. These physical and hydrologic reservoir system characteristics are: The magnitude of monthly inflow fluctuations, the relative storage-area relationships of the reservoirs, different evaporation rates at each reservoir site, and change in the monthly demand for water.

Inflow Fluctuations

The investigation of the influence of inflow fluctuations is performed using the two-reservoir system as modeled for Region I, Test A1. By the phrase "inflow fluctuations" is meant the magnitude and frequency of deviation of monthly inflows about their respective mean value. As suggested in Chapter V, the inflow fluctuations can be expected to affect the optimal operating policies as determined by RESEVAP.

Two sets of test runs were made, denoted as Test B1 and Test B2. Test B1 used as inflow the mean value of the ten-year period for each reservoir (2353 cfs-days for Reservoir 1; 3847 cfs-days for Reservoir 2). Thus, the inflows to Reservoirs 1 and 2 are constant for each month of the 10-year period. Inflows for Test B2 are the monthly averages based on the 10-year period - each year has the same sequence of 12 monthly inflows for each reservoir. Display 4, Appendix D shows the yearly inflow sequence for Test B2.

Table VII-1 shows the inflow characteristics for Tests B1, B2 and for convenient reference, the original inflows (as used for Test A1) for Region I from Table IV-4. As expected, the Test B1 inflows show no fluctuation while the original inflows show the highest, with respect to the minimum and maximum values and the standard deviation from the mean value.

TABLE VII-1
Inflow Characteristics, Region I (cfs-days)
Tests B1, B2 and A1

		Test B1	Test B2	Test A1
Reservoir 1	avg. inflow	2,353	2,353.1	2,352.5
	min. inflow	2,353	48	0
	max. inflow	2,353	8,695	48,514
	std. deviation	0	2,818.3	6,928.6
Reservoir 2	avg. inflow	3,847	3,847.2	3,847.2
	min. inflow	3,847	294	0
	max. inflow	3,847	9,399	48,556
	std. deviation	0	3,526.7	8,131.1

Summaries of the results for Tests B1, B2 and, for convenience, A1 are shown for Objectives 1, 2 and 3 on Tables VII-2a, VII-2b and VII-2c, respectively. It is noted that for all three objectives, Test B1 produces the highest evaporation losses, followed in succession by Test B2 and Test A1. Evaporation losses are highest for the test runs with the lowest standard deviation (Test B1), and lowest for the test runs with the highest standard deviation (Test A1). The evaporation reduction efficiency, as discussed in Chapter V for Test D1, is shown for the Objective 3 test runs on Table VII-3. Consistent with the results of Test D1, the evaporation reduction efficiency is higher for those test runs with the higher values of standard deviation. Refering to Tables VII-2a, VII-2b and VII-2c, it is seen that the average storage for both reservoirs decreases from Test B1 to Test B2, and from Test B2 to Test A1, as does the total evaporation loss. This is expected, since lower evaporation losses are in direct correspondence with lower storage levels. Apparently, the effect of the larger inflow fluctuations is to enable the optimal operating policy to keep the reservoirs at lower storage levels, thus reducing the evaporation.

Insofar as the results of the Region I test runs can be generalized, there appears to be a limit above which greater inflow fluctuations, as indicated by larger values of standard deviation, begin to increase the total spill loss. Test B2 consistently produces the lowest values of total spill, while Test A1 results in much higher values. The values of total water loss also follow the same pattern, being dominated by the changes in total spill rather than total evaporation. The only exception to these observations is the test runs for Objective 1 (Table VII-

Table VII-2a

Tests B1, B2 and A1; Objective 1, Region I

(all values in ac-ft)

		Test B1	Test B2	Test A1
System I	total evap.	97,009	95,546	92,702
	total spill	268,951	258,237	230,963
	total loss	365,960	353,784	323,664
	av. storage, Res. 1	2,008	1,208	12,533
	av. storage, Res. 2	119,101	114,270	86,579
System II	total evap.	96,491	95,147	86,431
	total spill	269,469	258,637	253,233
	total loss	365,960	353,784	399,664
	avg. storage, Res. 1	400	350	10,471
	avg. storage, Res. 2	120,724	115,004	79,788

Table VII-2b

Tests B1, B2 and A1; Objective 2, Region I

(all values in ac-ft)

		Test B1	Test B2	Test A1
System I	total evap.	153,719	148,355	113,062
	total spill	136,585	125,979	183,570
	total loss	290,305	274,334	296,632
	avg. storage, Res. 1	62,783	55,758	35,958
	avg. storage, Res. 2	119,074	115,965	82,611
System II	total evap.	153,664	148,320	113,332
	total spill	136,641	126,014	183,287
	total loss	290,305	274,334	296,619
	avg. storage, Res. 1	61,446	55,400	36,708
	avg. storage, Res. 2	120,082	116,379	81,914

Table VII -2c

Tests B1, B2 and A1; Objective 3, Region I

(all values in ac-ft)

		Test B1	Test B2	Test A1
System I	total evap.	151,105	145,662	108,245
	total spill	139,048	128,672	188,387
	total loss	290,152	274,334	266,632
	avg. storage, Res. 1	58,783	50,992	26,558
	avg. storage, Res. 2	120,685	118,696	90,160
System II	total evap.	152,609	146,230	107,827
	total spill	137,544	128,104	188,792
	total loss	290,152	274,334	296,619
	avg. storage, Res. 1	59,929	51,150	24,325
	avg. storage, Res. 2	121,512	119,265	93,520

Table VII-3

Ratio of Avg. Evap. Rate to total Evap. Loss

Objective 3, Region I

	Test B1	Test B2	Test A1
System I	$3.34\ 10^{-5}$	$3.47\ 10^{-5}$	$4.67\ 10^{-5}$
System II	$3.31\ 10^{-5}$	$3.45\ 10^{-5}$	$4.68\ 10^{-5}$

Table VII-2b

Tests B1, B2 and A1; Objective 2, Region I

(all values in ac-ft)

		Test B1	Test B2	Test A1
System I	total evap.	153,719	148,355	113,062
	total spill	136,585	125,979	183,570
	total loss	290,305	274,334	296,632
	avg. storage, Res. 1	62,783	55,758	35,958
	avg. storage, Res. 2	119,074	115,965	82,611
System II	total evap.	153,664	148,320	113,332
	total spill	136,641	126,014	183,287
	total loss	290,305	274,334	296,619
	avg. storage, Res. 1	61,446	55,400	36,708
	avg. storage, Res. 2	120,082	116,379	81,914

Table VII -2c

Tests B1, B2 and A1; Objective 3, Region I

(all values in ac-ft)

		Test B1	Test B2	Test A1
System I	total evap.	151,105	145,662	108,245
	total spill	139,048	128,672	188,387
	total loss	290,152	274,334	266,632
	avg. storage, Res. 1	58,783	50,992	26,558
	avg. storage, Res. 2	120,685	118,696	90,160
System II	total evap.	152,609	146,230	107,827
	total spill	137,544	128,104	188,792
	total loss	290,152	274,334	296,619
	avg. storage, Res. 1	59,929	51,150	24,325
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	Test B1	Test B2	Test A1
System I	$3.34\ 10^{-5}$	$3.47\ 10^{-5}$	$4.67\ 10^{-5}$
System II	$3.31\ 10^{-5}$	$3.45\ 10^{-5}$	$4.68\ 10^{-5}$

2a). Here both water loss components decrease in succession from Test B1 to B2 to A1.

Displays 1 and 2, Appendix H, show the tabular and graphical presentations of the Test B1 operating policy for the System II, Objective 3 test run. Note how the optimal policy reaches an "equilibrium" condition in January, 1963 and then repeats the following 12 month pattern each year.

Storage-Area Curves

The next reservoir system characteristic to be studied is the effect of changing the storage-area relationship, which is representative of changing a reservoir site location in an actual reservoir system. This study, labeled as Test G1, employs the same model setup as for Test A1, Region I. The one alteration is that the storage-area relationship for Reservoir 1 is exactly halved, i.e., for every storage level the corresponding surface area is exactly .5 times the surface area for Test A1. The plot of the storage-area curves for Test G1 are shown on Figure VII-1.

The value of A/ S for Reservoir 1 in Test A1 was constant at 1.86×10^{-2}, because of the linear storage-area relationship. Now the value is .5 times this, or 9.30×10^{-3}. The initial value of $\Delta A/\Delta S$ for Reservoir 2 remains the same at 1.15×10^{-2} (see Figure IV-2). For Test A1, Reservoir 1 has the largest initial value of $\Delta A/\Delta S$ and, according to the "principle of continuous release," water is drawn from Reservoir 1 first and continuously, until it is empty. For Test G1, however, Reservoir 2 has the largest initial value of $\Delta A/\Delta S$ and one should expect that releases should be made continuously from Reservoir 2.

Displays 1 through 4, Appendix I, show the optimal operating policies for System II, Objective 3 for Tests A1 and G1. Note that the policy for Test G1 is just the reverse of that of Test A1 during the first 59 months of no spill when Objective 3 reduces to minimizing cumulative evaporation. That is, Reservoir 2 is being drawn down before Reservoir 1. This is as anticipated from the respective initial values of $\Delta A/\Delta S$ for Reservoirs 1 and 2. Reservoir 2 is not able to reach zero storage due to the periodic large monthly inflows and also because of the approximations induced by the discretization of the storage in Reservoir 1. Large releases are made from Reservoir 1 only when it is full (to deter the occurence of spill) or when Reservoir 2 is near empty. A summary of the results of Tests G1 and the corresponding Test A1 results are displayed on Table VII-4.

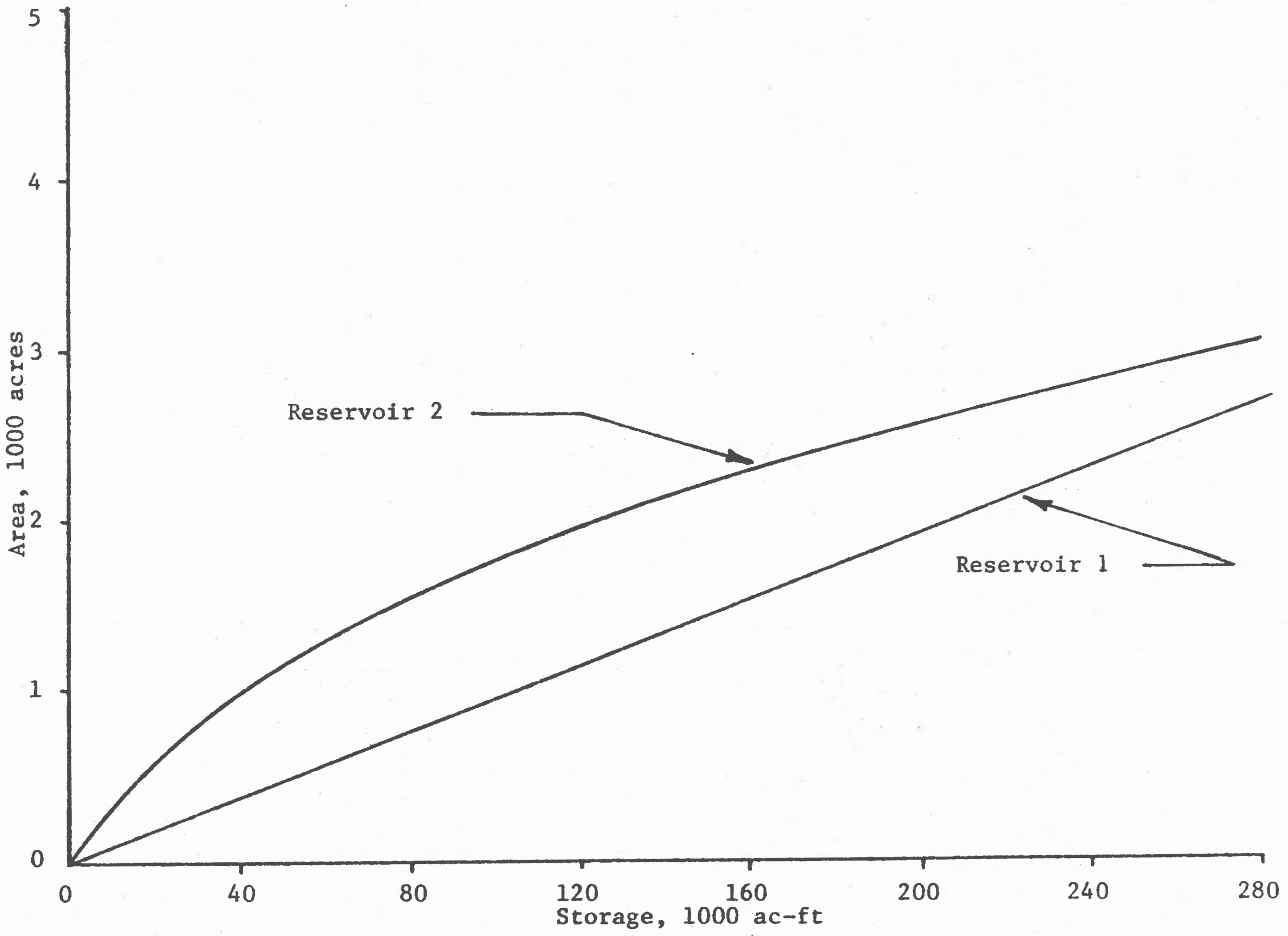


Figure VII-1

Storage-Area Curves, Test G1

Table VII-4

Tests G1 and A1; Objective 3, Region I

(all values in ac-ft)

		Test G1	Test A1
System II	total evap.	90,109	107,827
	total spill	205,182	188,792
	total loss	295,291	296,619
	avg. storage, Res. 1	56,121	24,325
	avg. storage, Res. 2	64,097	93,520

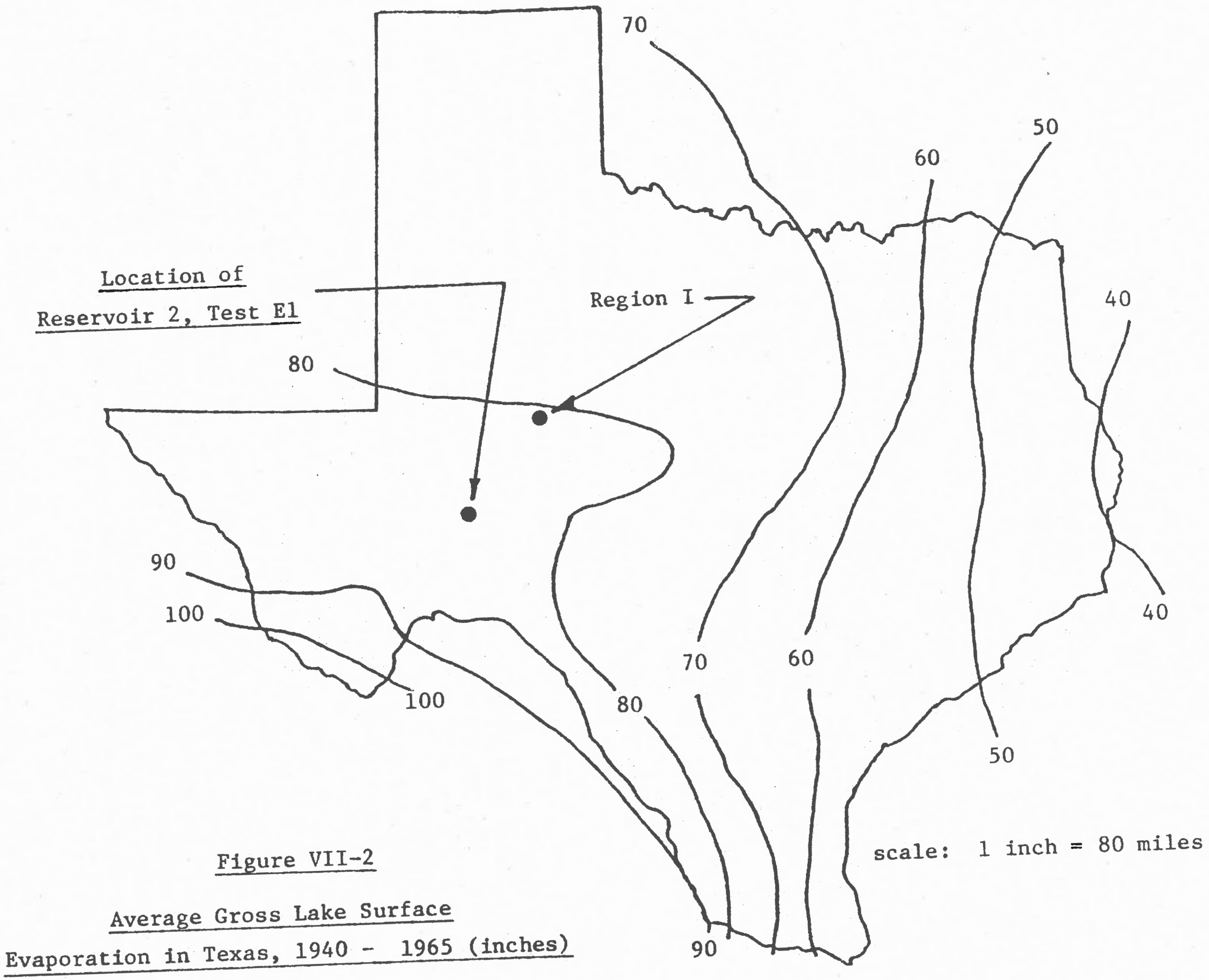
As evidenced by Display 1, Appendix I, the operating policy during the first 59 months is to keep Reservoir 1 as full as possible. Thus the operating policy during these months, which is to reduce evaporation, is in accordance with the objective of minimizing spill - keep the upstream reservoir as full as possible. The higher average storage in Reservoir 1 for Test G1 as compared to Test A1 also indicates this. It can be generalized, then, that for certain combinations of upstream and downstream reservoir shapes (storage-area relationships), the objective of minimizing evaporation need not be in opposition to the objective of minimizing spill.

Comparing total evaporation losses for Test A1 and Test G1, it is observed that Test G1 achieved about 16% reduction in evaporation losses, due to the reduction of surface area of Reservoir 1. The total surface areas of both reservoirs for Test A1 are 1,488 acres for Reservoir 1 and 1,962 acres for Reservoir 2, at their respective maximum storage levels. For Test G1, the total surface areas are 744 acres for Reservoir 1 (.5 of Test A1 area) and 1,962 acres for Reservoir 2. Comparing the total reservoir system surface area of Test G1 and A1, there is a 22 % reduction in surface area for Test G1. This 22% reduction in surface area produces only a 16% reduction in evaporation. The reason for this is that as evaporation is reduced, the total storage in the system is likewise increased. This additional water remaining in the sytem causes in turn greater evaporation losses, which reduce the decrease in evaporation to something less than the decrease in total surface area.

Evaporation Rates

Up to this point, all of the tests conducted in ths study have used the same monthly evaporation rates for Reservoir 1 and Reservoir 2. Thus, the influence of different evaporation rates at each reservoir has not been previously considered. The test runs discussed herein, collectively called Test E1, examine the differences caused by increasing the monthly evaporation rates for Reservoir 2.

Test A1, Region I is selected as the study to which Test E1 will be compared. The same data setup is used, except that Reservoir 2 is hypothetically



scale: 1 inch = 80 miles

Figure VII-2

Average Gross Lake Surface Evaporation in Texas, 1940 - 1965 (inches)

Table VII-5

Monthly Evaporation Rates, Test E1

(in./unit area)

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Reservoir 1	5.02	4.00	2.45	2.12	2.32	4.02	4.48	4.08	7.28	8.68	9.54	6.59
Reservoir 2	5.42	4.40	2.83	2.52	2.72	4.42	5.08	4.68	7.88	9.28	10.14	7.19

Table VII-6

Monthly Demand Sequence, Test F1A (ac-ft)

OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
5,100	5,100	5,100	5,100	5,100	5,100	10,100	13,200	16,300	13,200	13,200	13,200

moved to a location about 60 miles to the southwest, where the annual gross evaporation is about 6 inches greater than for Region I (see Figure VII-2). The new monthly evaporation rates for Reservoir 2 are shown in Table VII-5, along with the original monthly evaporation rates for Reservoir 1. The months October through March have an evaporation rate increase of .4 inches, while the months April through September have an increase of .6 inches, making the yearly increase 6 inches for Reservoir 2.

Two test runs are made for Test E1 - System I and System II, both with Objective 3. A summary of these test runs and the comparable test run from Test A1 are presented in Table VII-7.

TABLE VII-7

Tests E1 and A1; Objective 3, Region I

(all values in ac-ft)

		Test E1	Test A1
System I	total evap.	116,278	108,245
	total spill	180,626	188,387
	total loss	296,904	296,632
	avg. storage, Res. 1	28,250	26,558
	avg. storage, Res. 2	87,324	90,160
System II	total evap.	116,325	107,827
	total spill	180,579	188,792
	total loss	296,094	296,619
	avg. storage, Res. 1	25,654	24,325
	avg. storage, Res. 2	91,449	93,520

Tests E1 and A1 showed very similar operating policies, with the only deviation being that slightly less water was kept in Reservoir 2 for Test E1 because of its higher monthly evaporation rates. This is evidenced by the fact that for Test E1, the fraction of the total average storage in Reservoir 1 (24.4% for System I; 21.9% for System II) is higher than for Test A1 (22.7% for System I; 20.6% for System II). If the operating policy for Test E1 was identical to Test A1, i.e., each reservoir release the same fraction of the monthly demand for each test, then the average storage in Reservoir 1 would be expected to be the same, since Reservoir 1 would thus make the same releases, as well as be subject to the same inflow and evaporation losses. The fact that the average storage in Reservoir 1 is greater for Test E1 indicates that a larger portion of the monthly demands are drawn from Reservoir 2.

With respect to the total water loss, it is noted from Table VII-7 that Tests E1 and A1 are virtually equivalent. Test A1 has a lower evaporation loss which is offset by an increase in total system spill. This observation has implications in actual reservoir system operation. For a reservoir or system of reservoirs subject to occasional or periodic spill, attempts to reduce evaporation by applying a monomolecular film, eliminating shallow areas of the reservoir, etc. and thereby decreaseing the evaporation rate at one or more of the reservoirs may not be fruitful. The savings in water from evaporation reduction can be partially or wholly nulified by increases in reservoir spill.

Monthly Demand For Water

The problem of diminishing water supplies during extended draughts is often encountered by water use planners. Attempts to alleviate this problem often involve the implementation of water use curtailments. For the case of surface water reservoirs serving as a source of water, the intent in water use curtailment is to keep water in the reservoirs for future use if water shortages continue.

In this study, two test runs, Tests F1A and F1B are made which examine the effectiveness of water use curtailment in conserving water. Test F1A is identical to Test A1, Objective 3 for Region II, with the exception that the monthly demand has been increased, as shown on Table VII-6. Test F1B is the same as Test F1A, except that in the first year of the study, a reduction in the monthly demand has been implemented and the demand sequence for this year is the original demand sequence shown on Table IV-6. The total reduction in demand over the first year is 1,800 acre-feet, thus this much water is intended to be conserved for future use. Table VII-8 presents the results of Tests F1A and F1B for System II.

TABLE VII-8

Test F1; Objective 3, Region II

(all values in ac-ft)

		Test F1A	Test F1B
System II	total evap.	81,879	84,780
	total spill	91,039	89,938
	total loss	172,918	174,718
	avg. storage, Res. 1	23,204	31,121
	avg. storage, Res. 2	136,036	129,357

Because of the reduction in monthly demand the first year, Test F1B begins the remaining nine years of operation with additional water in storage (approximately 1,800 acre-feet, neglecting the increased evaporation losses during the first year). Using Objective 3, RESEVAP determines the optimal operating policy to minimize the total water loss, which in effect is the policy to maximize available water. Therefore, the amount of the 1,800 acre-feet remaining for future use is also maximized by the policy as determined by Objective 3. Table VII-8 shows that, after 10-years operation, the net effect of the demand reduction during the first year is to actually increase the total water loss. The total evaportion loss increased by 2,901 acre-feet due to the increased storage levels while the total spill decreased by only 1,101 acre-feet.

Displays 1 through 4, Appendix J show the operating policies for Tests F1A and F1B. Comparing displays 1 and 3, it is seen that in October, 1966 the reservoir system storage is nearly equal for Tests F1A and F1B. After this month the storage in Test F1A gradually becomes larger. After the first year, Test F1B starts out with nearly 1,800 acre-feet of additional water in storage which gradually diminishes until October, 1966, at which time no additional water remains. The increase in reservoir storage levels caused by the addtional water in storage create an increase in evaporation, the undesirable result being the eventual depletion of the water so saved. For this additional water to be beneficially used, it must be drawn from storage before October, 1966.

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CHAPTER VIII
SUMMARY AND CONCLUSIONS

Study Purpose

This research project has been an effort to fulfill the need for the investigation of evaporation losses as an integral part of reservoir system operation. The relative importance of evaporation reduction was evaluated for a two-reservoir system at three distinct geographic locations and in the context of overall water conservation.

Model Development

After a review of the existing simulation and optimization models for reservoir system modeling, it was decided that a computer model should be developed specifically for this research, tailored to fit the needs of an evaporation reduction study. The model so developed (RESEVAP) utilizes a DP algorithm applied to a two-reservoir system incorporating a single state variable. The model is capable of simulating the two-reservoir system in parallel or in series, and can optimize over any of three possible objective functions: minimize cumulative evaporation, minimize cumulative spill, or minimize the cumulative sum of evaporation and spill. The various methods of evaporation calculation were considered and the most practical method, utilizing pan evaporation data, was employed in the computer model.

Evaporation Reduction Theory

The principles governing evaporation minimization in a two-reservoir system were then investigated. It has been concluded that evaporation losses are minimized when the reservoir with the highest value of $\Delta A/\Delta S$ is drawn from first and continuously until it is empty. Deviations from this rule occur when the evaporation rates are negative, in which case the net gain of water is to be maximized. Also, the "principle of continuous release" may not be followed when storage levels can be further reduced at certain periods by forcing a system spill.

It is expected that the "principle of continuous release" also applies to reservoir systems involving more than two reservoirs, each reservoir being drawn from in succession, according to their respective values of $\Delta A/\Delta S$. The practical value of such an operating policy is questionable, however. In most reservoir systems, especially those serving multiple purposes, it is infeasible to allow a reservoir to be drawn from until it is empty. It may be that some reservoir systems have some degree of flexibility in regards to the maintenance of target storage levels. To the extent that releases can be made without causing extreme deviation from required storage levels, the "principle of continuous release" may be utilized to achieve minimum evaporation losses.

Test Summaries

The following outline summarizes each of the tests conducted in this research project:

Test A

Purpose - Evaluate evaporation reduction policies in the context of total water conservation.

Results - Policies which minimize evaporation alone greatly increase water loss, except in humid regions.

Test B

Purpose - Evaluate effects of inflow magnitude and fluctuations on evaporation reduction policies.

Results - Greater fluctuations decrease evaporation losses and increase system spill.

Test C

Purpose - Determine basic operating policies using HEC-3.

Results - Total water loss for the basic operating policies the same as for optimal operating policies.

Test D

Purpose - Quantify regional evaporation losses and verify "principle of continuous release."

Results - "Principle of continuous release" followed except in periods when rainfall exceeds evaporation.

Test E

Purpose - Investigate effects of differing evaporation rates at each reservoir.

Results - Different evaporation rates of minor importance with respect to operating policies for evaporation reduction.

Test F

Purpose - Investigate effects of water use curtailment.

Results - For the reservoir system as modeled, a water use curtailment increased total water loss over the 10-year period.

Test G

Purpose - Investigate different storage-area curves.

Results - Different storage-area curves significantly change the optimal operating policies.

Test H

Purpose - Determine reservoir system firm yield.

Results - Firm yield increased for operating policies which consider system spill as well as evaporation losses.

Evaporation Reduction

The two-reservoir system was modeled to simulate hydrologic and climatic conditions in each of three geographic regions. They are catagorized as Region I, arid; Region II, semi-arid; and Region III, humid. Evaporation losses were most severe in Region I, followed by Region II and Region III in succession. As modeled, Region III actually showed negative evaporation losses, due to the large amounts of precipitation in that region. The operating policies for minimizing evaporation in each region confirmed the proposed "principle of continuous release."

With respect to the potential for evaporation reduction, operating policies in both Regions I and II could be followed which resulted in considerable reduction of evaporation losses, as compared to the basic operating policy of maintaining a constant percentage of total storage in each reservoir (as determined by using HEC-3). Because of the offsetting factors of impractical operating policies and increased system spill, evaporation reduction via release regulation would seem desirable only in situations of complete flexibility in reservoir system operation and in systems with only minor spill losses.

Total Water Conservation

Of major importance in the mutual comparison of the three regions was the adjustment of the 10-year inflow sequences such that each had the same mean value, and thus the same total quantity of inflow over the 10-year period. Due to regional differences in inflow fluctuations, each region required a different amount of conservation storage to meet the chosen monthly demand sequence. The major distinguishing factors of each region, then, were the inflow fluctuations, required conservation storage and monthly evaporation rates.

In all three regions the reservoir system spill loss was of greater magnitude than the evaporation loss. In all test runs for Regions I and II with system spill, minimizing evaporation losses resulted in greater total water loss than the other two objectives. Because of the negative evaporation losses in Region III, minimizing evaporation losses proved to be as beneficial as the other two objectives of minimizing spill or total water loss.

Optimal Operating Policies

With respect to the underlying goal of water conservation, it has been shown that, except in situations of no reservoir system spill, operating policies which minimize evaporation alone are undesirable. This is evidenced by increased total water losses and smaller quantities of firm yield, as compared to operating policies which consider system spill in the objective of water loss minimization.

By comparing the results of test runs utilizing Objectives 2 and 3, and the test runs using HEC-3, it is evident that there is no unique optimal policy with respect to the minimum total water loss. Rather, there exists a "compensation range," in which there is a direct tradeoff between evaporation and spill losses. Any operating policy within this range is optimal, and it may be that existing reservoir system operating constraints dictate that certain of these optimal policies could be followed more easily than others.

Physical and Hydrologic Characteristics

According to the inflow data utilized in this research the magnitude of inflow fluctuations present in each of the regional inflow sequences appeared to effect the ability of the reservoir system to minimize evaporation losses. A higher degree of fluctuation resulted in the ability of the optimal operating policy to maintain lower average storage levels and thus lower evaporation losses.

The relative positions of two reservoirs in series also have an influence on operating policies which minimize cumulative evaporation and/or spill. For the situation of the upstream reservoir having higher values of $A/\Delta S$, policies which minimize evaporation are in opposition to the objective of reducing system spill. This is because water is transferred into the downstream reservoir to minimize evaporation losses. For the reverse situation, however, water is kept upstream to minimize evaporation as well as spill. The latter situation is more common, since downstream reservoirs are usually in flatter terrain and experience higher increases in surface area for an increase in storage, resulting in higher values of $A/\Delta S$.

The inclusion of different evaporation rates at each reservoir did not produce major changes in the optimal operating policies. It can be concluded that the effort to obtain exact evaporation loss rates at each reservoir site is only justified for the purposes of determining accurate quantities of firm yield, critical period storage levels, etc., such as in a reservoir system simulation study.

The concluding studies in this research project examined the effect of reducing the monthly demand for a period of time to conserve water. It was shown that for the conserved water to be effectively used, it must be released from storage before it is lost to future evaporation.

Study Limitations

The major limitation in this research project has been reliance on the selected 10-year historical inflow sequences as being representative of the characteristics of each region. It is likely that the use of longer historical inflow records will result in somewhat different operating policies. Also, runoff records from gaging stations in other geographic locations may possess characteristics not investigated in this study.

Another limitation in this research project was the modeling of a multiple reservoir system composed of only two reservoirs. As more research is devoted to the modeling of multi-reservoir systems using optimization routines, greater insight into the role of evaporation losses in reservoir systems may be obtained. Still other, less important, limitations have been the use of constant monthly evaporation rates each year and the exclusion of estimates of evaporation losses from water in transit from the upstream to the downstream reservoir.

Concluding Remarks

The fundamental purpose of any surface water reservoir or system of reservoirs is to store water for future use. Except for that portion of reservoir storage devoted to flood control, it is desirable to keep storage levels as high as possible, whether the reason is to maintain maximum head for power generation, adequate surface area for recreational use, or simply to maintain adequate conservation storage for maximum firm yield. This fundamental purpose is often in direct contradiction to the goal of evaporation minimization, which is achieved by maintaining low storage levels. Therefore, in consideration of all the information ascertained from this research project, it is felt that the objective of evaporation minimization will usually be of secondary importance with respect to other reservoir system operating criteria and constraints.

PART 2 - SYSTEM SIMULATION STUDY

CHAPTER I

INTRODUCTION

Objective

The objective of this study is to assess the potential for conservation of water through modifications in the design or operation of existing and proposed reservoirs. Recognizing that the management of water and the manner in which water is used vary with hydrologic, climatological and physical conditions, a variety of these factors is studied.

General Approach

It is recognized that the design and operation of reservoirs are constrained in so many ways that there is often little opportunity to modify either the design or operation without impinging on legal rights or vested interests. Nevertheless, the many wasteful conditions that result from these constraints must be overcome if the water resources of a region are to be utilized to their fullest, as appears to be a necessity in some regions. Accordingly, this study examines the capability of conserving water on the premise that these constraints can eventually be removed in a manner satisfactory to all. The results of the study can then be used to determine the gain that is possible under altenative plans of management.

It is considered that practical results can best be obtained through the use of actual project data. Accordingly, three projects were selected for the purpose of obtaining reservoir physical data, streamflow data and a variety of demand patterns in humid, semi-arid and arid regions. While three projects cannot encompass all the conditions and combinations of conditions that exist, it is considered that these projects and variations introduced reasonably represent most of the situations encountered.

The optimal yield or maximum conservation under each alternative management plan is obtained through successive approximations in detailed simulation of the reservoir operation for the period of recorded streamflows, using computer program HEC-3, "Reservoir System Operation for Conservation."

Project Examples

Three project examples have been selected to represent a broad spectrum of conditions and problems in reservoir management.

A system of four reservoirs in the fairly arid region of west Texas was selected for one example. Reservoir configuration, characteristics and inflows were obtained for the four reservoirs of the upper Colorado River basin of Texas, as listed in Table 1. While these reservoirs represent only a small part of the water resource system of that basin, they are used as though they constitute a complete system for using water as necessary for local needs. Thus, it is not intended to conform to the legal and institutional constraints that exist, but rather, for the purpose of this study, to examine the operation from the standpoint of the most effective conservation practice from a simplified hypothetical standpoint.

In connection with these four reservoirs, a groundwater operation is hypothesized in order to assess the potential impacts of conjunctive use of groundwater and surface water. This system was studied to determine:

a. Conservation potential through different distributions of stored water among the four reservoirs.
b. Conservation potential through different plans of conjunctive use of groundwater.

The second project selected is Pine Flat Reservoir in a semi-arid region of California. This reservoir is located in a narrow canyon and is operated primarily for flood control and irrigation, where water rights greatly exceed normal annual streamflows. Even in very wet years, most of the water is usable. Of course, the entities holding junior rights cannot economically develop their farming operations to a high degree, since years of no water would be a heavy financial drain under a high-capital-investment type of operation. Much of the water in wet years is used in irrigated pasture and similar low-income endeavors. The operation of Pine Flat was studied to determine:

a. Conservation potential through different mixes of firm supply for high-capital-investment uses and secondary supply for low-investment uses.
b. Conservation potential through increasing the size of the reservoir and thus reducing the amount of wasted water in wet years.
c. Conservation effected because of the location of the reservoir in a narrow valley as contrasted with location in a broad valley exposing larger areas to evaporation losses (a design consideration).
d. Conservation through increasing the yield by simply accepting damaging shortages during severe droughts.

The third project is Sam Rayburn Reservoir in the humid east Texas, which is an expansive lake with large storage capacity and large inflow. There is a power plant at the dam. The operation of this reservoir was studied to determine:

a. Increased yield obtainable by a two-level water demand (with primary supply highly dependable and secondary supply curtailed during droughts) as contrasted to a one-level firm supply.
b. The effects of this on evaporation losses and power generation.

Project Data

In order to base studies on realistic conditions, actual physical data on each of the selected projects were used. This includes elevation-storage-area relationships, power-plant characteristics, and storage allocations. Evaporation rates used are those specified by the operating agency or by the state Department of Water Resources. Streamflows are obtained from U.S. Geological Survey streamflow station data, adjusted if and as necessary to the pertinent locations for each reservoir. Care was exercised to assure that the periods for which flows were selected were the entire periods for which such flows would represent inflows to the reservoir site under unregulated conditions.

Demands placed on each system were tailored as much as possible to the actual patterns of uses in each case. These demands were then varied in order to obtain optimum yield for each system and each system alternative considered.

Computation Procedure

Computer program HEC-3, "Reservoir System Operation for Conservation," performs a highly accurate and detailed simulation of the operation of one or more reservoirs, using a monthly computation interval. Monthly inflows for each pertinent location must be supplied along with monthly demands where pertinent. Demands can be specified as flows to be supplied when adequate water is in storage above a reserve or buffer level, and, if desired, priority demands to be supplied even when storage is below the buffer pool level. The operation is controlled by a system of target levels at each reservoir for the end of each month. Releases are made as required to meet downstream flows in such a way as to keep all reservoirs in the system at the same target level number to the extent possible without wasting water until flood releases are required.

These levels are specified in terms of storage at each reservoir so as to define the desired distribution of system storage among the individual reservoirs. The bottom level (level 1) is minimum pool, below which no water is released from storage. The second level is the top of the buffer zone, within which only priority releases are made. The top two levels define flood control space, within which full flood releases are made so as not to exceed flood flow targets downstream.

Since the computation is done on a monthly basis, travel time within the system is neglected. No channel routing or channel loss provisions are used, but there are provisions for diversions and return flows. Computation proceeds from upstream to downstream. At each control point, flow requirements and channel capacities are satisfied by drawing on upstream reservoirs so as to maintain storages in balance as specified by the levels. When needs can be satisfied by only certain reservoirs or when large inflows occur only at certain reservoirs, the system can temporarily be out of balance, but subsequent relases usually return the system to the desired balance in a short time.

Reservoir evaporation is computed by applying monthly values of net evaporation in inches (or millimeters, if desired) to the average lake area for each month. Power generation is computed by multiplying the power release (up to turbine capacity for each head) by the average head for each month and an efficiency and conversion factor. For this computation, tailwater elevation can be specified as a function of outflow or, if backwater from a downstream reservoir controls, as the elevation of the downstream pool.

Once the system configuration and characteristics are specified as input data, along with initial conditions, inflows, evaporation rates and flow requirements, the computation iterates each month until the specified period of operation is complete. Pertinent storages, flows, evaporation, diversions and power quantities for each month are printed out, along with summaries at the end. This makes it easy to assess the results and the internal relationships that affect the overall results.

An internal optimization routine determines the maximum yield at any point in a system such that conservation storage is fully utilized and no shortages occur. This is an interaction routine that keeps track of accumulated demands since the system was last full and unused storage (in the case of demands too low) or total shortage since the last time of full storage (in the case of demands too high). The lowest ratio of unused storage to accumulated demand or the highest ratio of accumulated shortage to accumulated demand is used to adjust the demand for the successive iteration. The routine is very rapidly converging (two or three iterations, usually).

CHAPTER II

CASE STUDY - COLORADO RIVER SUBSYSTEM

Reservoir System

Figure 1 illustrates the configuration used in studying the four-reservoir system on the Colorado River basin of Texas. As indicated earlier, this group of reservoirs is upstream of several other reservoirs and is isolated in this study hypothetically in order to study certain conservation aspects without the complicating factors of downstream use and downstream water rights. Each reservoir has a minimum pool below which withdrawals are not made, and none has dedicated flood-control space. Area and capacity data are given in Tables 2 to 5.

Inflow Data

Inflow data for these reservoirs were obtained from U.S. Geological Survey records at four streamgaging stations listed in Table 6, whose locations relative to the reservoirs are shown in Figure 1. Since periods of record shown in Table 6 are not simultaneous and complete, values needed to complete records for the period 1948 to 1977 were estimated by use of a Monthly Streamflow Simulation computer program (MOSS) that performs multiple regression analysis and reconstitutes each missing value using all directly related values in the curent and preceding months. Inflows for each reservoir were then computed as linear combinations of streamflow station data as indicated in Table 7. Monthly inflows used are given in Tables 8 to 11.

Evaporation

Reservoir evaporation computations require consideration of the difference between lake evaporation at any time and the evapo-transpiration losses that would have occurred in the same area without the lake at that same time. This is referred to herein as net evaporation loss, and it is expressed as inches depth over the average area of the lake during any specified period. Values of net evaporation for each month were obtained from a generalized study of evaporation and net evaporation by the Texas Water Development Board (now Department of Water Resources). These values are averages for each calendar month and are given in Table 12. Their values were applied to the current lake areas each month.

It should be noted that, once land has been inundated or cleared of vegetation, runoff characteristics change, so, even though some of the lake area may not be innundated at the time, the effects of the project in that bared area might be significant. However, there is no good technique for accounting for such effects. They are usually ignored in reservoir operation studies and are ignored in this particular study.

Demand Pattern

Since one of the variables stressed in the study of this particular system is the integration of surface and ground water management, the demand pattern used is one composed of a constant demand such as is approximated for municipal and industrial uses and a seasonal demand such as for irrigation. The hypothetical demand pattern used is given in Table 13. In two of the simulation studies, a constant demand pattern was used for comparison.

Case Study Objectives

The primary objectives of studying this system as stated earlier are:

a. Conservation potential through different distributions of stored water among the four reservoirs, and
b. Conservation potential through different plans of conjunctive use of ground water.

In studying the first objective, simulation computations for the 29 years of record were done two ways. The first simulation kept as much of the stored water as possible in the downstream reservoir and the remainder, if any, distributed among the three upstream reservoirs in proportion to the active storage capacity in each. Minimum pools were maintained in all four reservoirs. This is expected to minimize evaporation losses but to risk spills due to high intermediate runoff ocurring when storage in the downstream reservoir is high. The second simulation kept the stored water about evenly distributed among the four reservoirs in terms of ratios to their active storage capacities. The expectation is that this would reduce risk of spills but increase evaporation. A third simulation was subsequently made with only the downstream reservoir (in order to eliminate evaporation from upstream minimum pools).Results of these simulations are shown in Table 14 and discussed below.

Since reservoirs in this study are so large that they did not fill during the period of record, the study was repeated with similar reservoirs of reduced size. Comparison of these two series of simulations, shown in Table 14, sheds some light on the effects of over-sizing reservoirs in arid regions. This is discussed below.

In studying the second objective, two alternative plans of groundwater use were studied. The first is to serve municipal and industrial uses at a constant rate from groundwater pumping, which would require well fields with a total capacity corresponding to that rate. In this case, all of the remaining demand would be served from the reservoir system. The second plan is to serve a large portion of the total demands from groundwater pumping (at a maximum rate of 60 cfs) but only during drought periods. This would require extensive well fields but would decrease the average surface storage and correspondingly the evaporation. In both of these cases, reservoirs were operated in a balanced fashion; that is, stored water was distributed in proportion to the active storage capacity in each case, except that 75,000 acre-feet of reserve storage was held in the most downstream reservoir in the second case for use only during extreme droughts when well capacity is inadequate to serve the high irrigation demands. Results of the studies of these two plans for two different pumping amounts are given in Table 15 and discussed below.

Case Study Results

The net yields shown in Tables 14 and 15 are approximate, since the amount of shortage and residual storage experienced in the studies differs in different simulations. If the shortages were eliminated entirely by closer approximation of the zero-shortage yield, results shown would be slightly different. However, for the first objective studied, it can be seen that the evaporation loss is reduced by about 16 percent or 11 cfs (8,000 acre-feet per year). This is a substantial saving for simply redistributing the storage among the reservoirs. Of course, it should be kept in mind that this study ignores water rights as they exist and assumes that they are all downstream of the lowest reservoir. In actual practice, such an operation would be modified to assure availability of water where it is required. Nevertheless, substantial savings of water are possible. It can be noted that there is very large storage capacity in this system, and elimination of the three upstream reservoirs would actually increase the yield.

Results shown in Table 14 for reservoirs as constructed were adjusted for changes in storage for the period of record, because the reservoirs never filled. Consequently, the yield shown in the simulation depended to some extent on the use of water initially stored. In order to further check the effects of factors studied, sizes of reservoirs were reduced as shown in Table 14, and simulations repeated. In these cases, reservoirs filled and spilled, so the yield adjustment for storage change is not appropriate.

The decreased yield for larger reservoirs in the first two cases is due to higher initial storages used in the simulations and consequent higher evaporation losses. It is reasonable to conclude that, if operated similarly, the yields for the larger reservoirs would be at least as large as for the smaller reservoirs. It is apparent that they would not be appreciably larger, and that the smaller reservoirs are essentially as productive as the larger in this hypothetical example. In the third case (one reservoir only), heavy spills occurred at the smaller reservoir, resulting in reduced yield.

For the second objective studied, the variable use of groundwater was managed to approximate the same average over the 29 years of study as for the constant groundwater use. Delaying the use of groundwater until the reservoirs were drawn down reduced the average annual evaporation by 9 percent, or 6 cfs (4,300 acre-feet per year) for the low rate of groundwater use and 19 percent for a higher rate of groundwater use. Again, this is a substantial saving, but requires a large investment in well fields. Differences due to seasonal distribution patterns are shown in Table 15 where essentially the same average yield is shown for constant or seasonally varying demand patterns.

CHAPTER III

CASE STUDY - PINE FLAT RESERVOIR

Reservoir Data

General data for Pine Flat Reservoir are given in Table 1. Area and capacity data are given in Table 16. The reservoir is operated for flood control and water supply in accordance with storage criteria given in Table 17. The reservoir does not have a minimum pool below which withdrawals are not permitted, but it has never been drawn down completely.

Inflow Data

An excellent record of streamflows of Kings River at Piedra, a short distance downstream from Pine Flat Reservoir, has existed since the turn of the century. By use of a coefficient of 0.916, these records were used for estimating monthly inflows for 52 years from 1899 to 1951, the time that Pine Flat Reservoirs started storing water. These inflows are given in Table 18.

Evaporation

Lake evaporation estimates used in the operation of Pine Flat Dam and Reservoir are based on extensive studies of the seasonal variation of the relation of lake evaporation to pan evaporation at lakes where lake evaporation could be measured accurately (where inflows and outflows are small in relation to evaporation quantities). Monthly evaporation quantities used in this study were derived from averages of the pan evaporation recorded for each calendar month at Pine Flat Reservoir, multiplied by the corresponding pan coefficient, less average rainfall recorded at Pine Flat Dam for that month. This computation and resulting evaporation rates are given in Table 19.

Demand Pattern

Base studies using Pine Flat Reservoir a seasonally varying demand pattern. Hypothetical studies of an enlarged Pine Flat Reservoir and studies of operations with substantial shortages use a constant demand for convenience. The seasonal variation reflects the high use of irrigation water during the summer months and yet, because of the climate and rainfall patterns, substantial amounts of water during the remainder of the year. Seasonal variation factors are given in Table 20.

Case Study Objectives

As indicated earlier, objectives in studying the design and operation of Pine Flat Reservoir are to relate conservation potential to each of the following factors:

a. Different mixes of firm supply and secondary supply
b. Variations in reservoir size
c. Variations in area-capacity relationships
d. Acceptability of shortages during extreme droughts.

In studying the first factor, all available reservoir space below the flood-control pool up to 600,000 acre-feet were reserved for primary uses and the remainder was used for storage of water for all uses. When the reservoir recedes below 600,000 acre-feet in this hypothetical operation, only primary uses are accommodated. Data on this simulation are compared in Table 21, rows 1 and 6, with results of using all storage below the flood-control level for development of a single maximum firm yield. Findings are discussed below.

In studying the second objective, four sizes of reservoirs were used to determine firm yield. These ranged from the existing capacity of 1,001,000 acre-feet to 6,000,000 acre-feet. Data are shown in Table 21 (rows 2 and 7 to 9) and results are discussed below.

In studying the third objective, the area-capacity relationship of Sam Rayburn Reservoir described below (and shown in Table 22) was used in a simulation of the operation of Pine Flat Reservoir, using existing capacity and other existing conditions at Pine Flat. Data on this simulation are compared in Table 21 with those of the simulation for maximum yield under present operation criteria (rows 1 and 13). Results are discussed below.

In studying the last objective, the existing and largest hypothetical sizes of reservoir (1,001,000 and 6,000,000 acre-feet) were used for simulations with successively larger water demands. Data on these runs are compared in rows 2 to 5 and in rows 9 to 12 of Table 21. Results are discussed below.

Case Study Results

Not all of the firm-yield runs identified in Table 21 converged to exactly zero shortage with full use of reservoir space. Determinations of firm yield obtainable under any set of conditions are made iteratively, and it was decided to accept slight shortages in the interest of saving computation times. Nevertheless, results are very close to those obtainable with complete convergence.

With respect ot the first objective it was found that during the 52-year operation, an annual average flow of 1783 cfs could be supplied, 1022 cfs of which is firm yield and the remainder supplied under a total demand schedule of 2433 cfs with some shortages in every year. This compares with a firm yield of 1132 cfs average annual flow attainable every year if the entire reservoir, except for flood space, is used for firm supply only. Thus, by sacrificing 110 cfs of firm yield, 761 cfs of undependable yield is obtained. Some of this undependable yield can be used for crop irrigation in fields used intermittently, because heavy runoff during the spring during wet years can be forecasted as early as February and can be stored through the summer. Of course, such intermittent use would prohibit as great a degree of land development for farming as would be justified if the yield is firm.

As a matter of interest, none of the supplementary water was supplied in two of the 52 years. At least 1200 cfs of supplementary water was supplied in 11 years, at least 1000 cfs in 19 years, at least 800 cfs in 28 years and at least 400 cfs in 41 of the 52 years. It is obvious that this could provide a great conservation benefit under proper management as contrasted with an additional 110 cfs of firm yield only. The reservoir does operate with a high variable yield in practice.

In the case of the second objective, the results in Table 21 show that the firm yield increases 396 cfs from 1136 to 1499 cfs (32 percent) while the evaporation loss increases by only 12 cfs when storage capacity is changed from 1,001,000 acre-feet to 2,000,000 acre-feet. Increasing storage capacity from 2,000,000 to 4,000,000 acre-feet increases the firm yield by 250 cfs (22 percent of present-capacity yield) and evaporation by 20 cfs. Increasing storage capacity from 4,000,000 to 6,000,000 acre-feet increases firm yield by 185 cfs (16 percent of present-capacity yield) while increasing evaporation by 10 cfs. These increases in yield and evaporation are obtained through a reduction in spill. It should be kept in mind that a large part, if not most, of this spill is usable for low-income applications and is therefore not entirely lost.

Results of studying the third objective show that by increasing the area for each level of capacity to that which exists at Sam Rayburn Reservoir (see Figure 2), the yield was reduced from 1132 cfs to 993 cfs or about 12 percent, while the evaporation increased from 23 to 219 cfs, an increase by a factor of 9.5. Thus, while evaporation is only 2 percent of the yield as the reservoir exists, it would be 22 percent of the yield if the reservoir area were as flat as that at Sam Rayburn Reservoir. This emphasizes the importance from a water conservation standpoint of locating reservoirs in narrow canyons as contrasted to broad valleys or, at least, using deep versus shallow reservoirs.

The fourth objective demonstrates that some gain in yield can be obtained with the same storage facility if large shortages are occasionally acceptable. The gain in yield comes from reductions in spill and evaporation, and, in the case of the larger reservoir, reduction in evaporation is a substantial part. When the existing 1,001,000 acre-foot reservoir is used, as contrasted with the 6,000,000 acre-foot hypothetical reservoir,the gain is greater and almost entirely through reduction in spill. This method of obtaining increased yield has been used for irrigation water-supply projects, where frequent shortages of 10 percent of the annual yield are not serious and occasional shortages of 30 to 50 percent can be tolerated with substantial financial losses.

CHAPTER IV

CASE STUDY - SAM RAYBURN RESERVOIR

Reservoir Data

General data for Sam Rayburn Reservoir are given in Table 1. Area and capacity data are given in Table 22. The reservoir capacity is 4,442,000 acre-feet, which contains 442,000 acre-feet of flood control space throughout the entire year. Of the remaining 4,000,000 acre-feet of storage space, 1,145,000 acre-feet is reserved as a minimum pool for power production and other purposes.

Inflow Data

Inflow data for Sam Rayburn Reservoir were obtained from U.S. Geological Survey data for the station, Angelina River at Horger, Texas, which is now downstream of the reservoir. Data are available for the years of 1928 to 1950 prior to construction of the reservoir, and these flows were adjusted to represent reservoir inflows by multiplying by the drainage-area ratio of 0.99. Inflows used for the analysis are given in Table 23.

Evaporation Data

Net reservoir evaporation data for Sam Rayburn Reservoir were obtained, as in the case of the Colorado River reservoirs, from generalized studies made by the Texas Department of Water Resources. Average values for each calendar month for this location as used in the study are given in Table 24. It can be noted that these rates for a humid region are far lower than rates for the other regions and, in fact, negative in some months. Whenever natural vegetation and rainfall amounts are sufficient, it is possible and often likely that pre-project evapo-transpiration rates are higher than lake evaporation rates.

Demand Pattern

Demands for water uses in this humid region do not vary greatly seasonally. For this reason, a constant demand throughout each of the 22 years of study was used.

Case Study Objectives

Two objectives for this case study were, as indicated earlier:

a. To determine the increased yield obtainable through using a two-level demand, the first-priority level being satisfied in all years and the second-priority level being subject to shortages during drought years. In order to assure a firm yield of the high-priority demand in all years, the 1,273,000 acre-feet of space above minimum-pool level was reserved for this purpose. Whenever the pool dropped to within this range, second-priority demands were not served.

b. To assess the impacts of one-level versus two-level demand patterns on reservoir evaporation and power generation. The power plant has a capacity of 52,000 kilowatts and was operated for the purposes of this study with a plant factor of 1.0 and an overload factor of 1.15.

Case Study Results

Pertinent results of this study are tabulated in Table 25. As contrasted to the results for Pine Flat Reservoir, the gain in yield by going to a two-level demand pattern is not great in relation to the yield for a one-level demand pattern, considering the substantial loss in firm yield. While the total yield at Pine Flat went from 1132 to 1783, an increase of 58 percent, the firm yield decreased from 1132 to 1022, or only 10 percent. In the case of Sam Rayburn, the increase of total yield from 2445 to 2724 is only 11 percent, while the decrease in firm yield from 2444 to 2270 is 7 percent. There is almost no change in evaporation, and the gain in yield is due to a reduction in spill. This demonstrates that a two-level demand pattern is not advantageous in humid regions, especially where large reservoir capacities exist.

Power generation was not substantially impacted by the change in operation from a 1-level to a 2-level demand pattern. Average annual generation declined from 107 to 106 million kilowatt-hours, and there is, of course, greater variation in generation from year to year and season to season because of the demand fluctuations. In general, it can be stated that power generation decreases when the reservoir is drawn down faster and increases when spill at rates beyond power plant capacity decreases. Since more rapid draw-down (such as by use of a 2-level demand pattern) usually results in less spill, these factors compensate to some degree. If conservation of power generation (energy) were of primary concern rather than the conservation of water, it might well be wise to reserve some space below the flood-control pool and above the water-supply pool for releasing flows at full power plant capacity. This could maximize both the average power head and the total flow through the power plant.

TABLE 1
RESERVOIR DATA

Reservoir Name	Stream	Drainage Area (sq. mi.)	Conservation Capacity (ac-ft)	Flood Control Capacity (ac-ft)	Date Completed
Lake J. B. Thomas	Colorado River	934	202,300	0	Sept. 1952
Lake Colorado City	Morgan Creek	290	31,485	0	Sept. 1949
Champion Creek Reservoir	Champion Creek	203	41,620	0	April 1959
E. V. Spence Reservoir	Colorado River	4,140	488,760	0	Nov. 1969
Pine Flat Reservoir	Kings River, CA	1,545	1,000,000	476,000	Dec. 1954
Sam Rayburn Reservoir	Angelina River, TX	3,449	1,452,000	1,100,000	March 1965

TABLE 2

AREA AND CAPACITY DATA, LAKE J. B. THOMAS

Elevation (ft. msl)	Area, (acres)	Capacity, (acre-feet)
2175	0	0
2200	250	1,300
2210	1,270	8,000
2220	2,260	26,700
2230	3,220	55,000
2240	4,450	93,300
2250	6,240	147,000
2258	7,820	203,600
2264	9,100	255,000

TABLE 3

AREA AND CAPACITY DATA, LAKE COLORADO CITY

Elevation (ft. msl)	Area (acres)	Capacity (acre-feet)
2002	0	0
2024	20	320
2070	1,610	31,800
2073	1,830	37,300

TABLE 4

AREA AND CAPACITY DATA CHAMPION CREEK RESERVOIR

Elevation (ft msl)	Area (acres)	Capacity (acre-feet)
2005	0	0
2020	100	880
2030	220	1,200
2040	370	4,000
2050	580	8,700
2060	800	15,600
2070	1,070	25,200
2083	1,560	42,500
2091	2,040	56,800

TABLE 5

AREA AND CAPACITY DATA, E. V. SPENCE RESERVOIR

Elevation (ft msl)	Area (acres)	Capacity (acre-feet)
1788	0	0
1810	250	500
1820	750	6,000
1830	1,500	19,000
1840	2,600	40,000
1860	5,400	120,000
1880	9,500	267,000
1898	15,000	489,000
1908	18,000	664,000

TABLE 6

STREAMGAGING STATIONS
COLORADO RIVER, TX

U.S.G.S. Number	Name	Drainage Area (sq. mi.)	Period of Record
8119000	Bluff Creek nr. IRA Tx.	42.6	1948 - 1965
8120500	Deep Creek nr. Dunn, Tx.	188	1953 - 1977
8121500	Morgan Creek nr. Westbrook, Tx.	228	1954 - 1963
8122000	Graze Creek nr. Westbrook, Tx.	21.2	1954 - 1959
8123500	Champion Creek nr. Colorado City, Tx	158	1948 - 1959
8123800	Beals Creek nr. Westbrook, Tx. 973	973	1959 - 1977

TABLE 7

FACTORS FOR COMPUTING INFLOWS
COLORADO RIVER SYSTEM

RESERVOIR	STATION	FLOW MULTIPLIER
LAKE J. B. THOMAS	8119000	2.04
	8120500	2.04
	8121500	2.04
LAKE COLORADO CITY	8121500	1.16
	8122000	1.16
CHAMPION CREEK RES.	8123500	1.28
E.V. SPENCE RES.	8119000	2.25
(LOCAL RUNOFF)	8120500	2.25
	8123800	2.25

TABLE 8

MONTHLY INFLOWS IN CFS-DAYS
LAKE J. B. THOMAS

WATER YR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1949	3906	716	88	70	67	122	3135	2427	1544	644	376	55
1950	41	1582	169	82	310	21	151	3028	171	1678	1319	3083
1951	129	676	235	8	484	10	709	2036	3415	3871	1741	153
1952	0	61	4	2	5	171	286	62	41	3627	297	58
1953	158	2407	73	137	0	277	12	79	61	5372	641	944
1954	4823	4	2	6	4	0	2119	10601	149	119	751	0
1955	0	0	0	0	381	1242	0	19180	1030	1767	777	1969
1956	12042	0	12	12	65	0	257	2840	781	820	722	0
1957	73	8	108	0	4464	43	17656	42177	7407	651	190	373
1958	787	1122	45	55	65	73	2874	1183	1312	0	98	494
1959	73	53	41	29	90	37	33	245	5602	6428	43	0
1960	2234	18	126	59	39	33	12	65	4	5622	114	4
1961	3717	2	41	82	43	29	6	3860	12758	8368	6	1083
1962	169	1146	55	69	47	24	71	12	6654	690	71	35778
1963	322	84	100	82	51	20	718	6671	410	188	27	69
1964	36	849	27	57	27	11	2058	1203	975	0	67	1995
1965	27	4	12	51	10	0	7133	27669	4147	219	172	27
1966	1179	165	0	0	1	61	2142	2805	3660	277	2452	2156
1967	68	0	2	4	314	66	2882	30	28601	1001	259	693
1968	325	37	51	105	136	260	1089	10978	361	394	27	340
1969	0	1130	54	15	78	106	1224	10664	855	46	672	379
1970	444	60	235	76	167	166	1286	118	260	3	4	0
1971	29	0	0	0	0	0	0	4616	1092	676	21691	2802
1972	1463	169	150	155	154	33	117	2412	1237	699	20583	11300
1973	2834	998	174	199	2599	1362	5122	464	5610	1051	293	212
1974	60	71	90	67	74	31	440	592	700	0	1125	1455
1975	3076	688	263	155	818	151	622	26081	1082	3616	900	22945
1976	450	890	283	109	127	92	616	502	22	2405	169	445
1977	3154	233	236	188	500	116	8629	9904	476	97	331	11736

TABLE 9

MONTHLY INFLOWS IN CFS-DAYS
LAKE COLORADO CITY

WATER YR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1949	1899	380	35	1	1	8	631	1783	380	366	56	0
1950	28	757	63	0	0	0	18	606	54	862	25	1714
1951	0	244	154	0	0	1	0	2540	1362	1196	3	1
1952	0	0	3	0	3	0	0	31	16	2062	159	31
1953	1	801	4	0	0	0	0	57	15	2916	0	326
1954	1988	10	0	0	0	0	338	4281	49	68	434	0
1955	0	0	0	0	0	0	0	2700	305	897	430	1
1956	2873	0	0	0	0	0	187	1578	222	457	409	0
1957	56	5	64	0	0	19	8223	14577	2377	7	103	28
1958	466	535	0	0	0	0	378	291	241	0	1	135
1959	36	1	0	0	28	8	8	108	567	1276	20	10
1960	1168	11	43	1	0	0	8	36	2	1819	0	0
1961	725	0	4	2	0	0	0	1745	4853	4242	3	3
1962	30	318	0	2	0	1	2	0	924	151	0	16621
1963	79	7	10	7	6	7	13	1485	87	107	3	82
1964	12	387	0	0	0	2	3474	476	372	0	0	1016
1965	5	0	0	0	6	0	4529	10928	1909	109	43	26
1966	438	0	0	0	0	0	195	1552	947	31	6	1108
1967	71	0	0	0	176	20	2274	17	6417	404	54	295
1968	120	3	0	1	22	10	98	6197	92	111	0	2
1969	0	563	31	3	10	11	37	4591	332	26	381	0
1970	173	13	102	5	11	1	868	38	69	0	0	6
1971	16	0	0	0	0	0	0	1206	219	311	1776	0
1972	265	10	3	0	7	0	0	934	533	278	67	4129
1973	1212	414	1	0	981	21	3703	92	805	492	158	0
1974	4	0	0	0	13	0	95	340	258	0	83	377
1975	791	256	49	3	91	0	263	15453	612	543	184	12899
1976	217	380	100	0	11	2	161	181	20	730	29	0
1977	503	48	31	1	20	21	6237	5018	145	0	0	5913

TABLE 10

MONTHLY INFLOWS IN CFS-DAYS
CHAMPION CREEK RESERVOIR

WATER YR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1949	488	19	24	72	111	38	1276	2999	46	14	8	294
1950	22	20	35	50	40	22	262	1119	20	532	296	573
1951	13	20	49	45	51	42	32	4474	1765	787	10	10
1952	8	6	17	36	45	31	13	394	3	19	3	238
1953	6	69	15	15	19	24	13	150	3	596	220	265
1954	1074	5	5	14	10	8	122	5158	10	3	4	4
1955	12	3	5	8	65	4	4	3817	764	1372	22	10
1956	284	5	5	6	6	6	586	2340	768	6	0	0
1957	49	4	42	5	6	52	8626	8120	4828	9	56	1897
1958	298	55	14	17	18	19	23	147	6	8	508	179
1959	70	8	9	10	12	6	9	17	316	259	4	97
1960	129	8	29	21	41	20	11	48	2	692	170	97
1961	516	3	17	59	59	10	4	2208	316	1533	23	13
1962	11	125	7	46	45	20	8	0	774	20	35	89
1963	43	7	19	62	20	0	723	2013	1	3	59	9
1964	16	47	6	16	20	49	6	952	76	4	127	21
1965	15	3	5	10	9	47	12	4528	20	412	22	248
1966	472	14	4	7	11	24	1612	2139	21	8	202	85
1967	50	7	5	6	3	49	4	0	3518	1009	122	67
1968	35	18	19	26	13	17	16	4950	160	23	31	20
1969	5	35	41	39	22	19	935	3088	6	24	2	67
1970	66	8	38	46	26	39	7	0	5	5	43	498
1971	17	3	2	9	20	16	40	1862	5	567	64	87
1972	78	37	19	43	32	11	35	1517	91	380	225	154
1973	641	64	22	117	8	40	153	127	2	1141	24	107
1974	20	10	14	58	36	25	43	939	80	2	19	0
1975	189	70	36	199	38	14	10	7710	4534	1718	1603	907
1976	170	53	48	62	27	23	235	243	4	8	4	0
1977	147	19	22	80	31	45	5707	5469	46	5	890	1908

TABLE 11

MONTHLY UNREGULATED INFLOWS IN CFS-DAYS

E. V. SPENCE RESERVOIR

WATER YR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1949	10212	1075	375	532	803	390	5550	10821	3368	581	573	3854
1950	242	2204	524	649	666	161	7083	8642	639	1010	10251	4111
1951	237	1110	503	1170	1036	1683	1322	14447	3815	5164	5480	994
1952	45	180	89	135	668	681	925	1101	1164	4829	96	2041
1953	265	3206	278	451	207	621	1224	1159	586	5272	1193	5780
1954	5490	214	98	323	200	100	4983	29898	2408	0	309	0
1955	26	35	66	235	713	2387	428	40805	1054	1673	1106	7986
1956	16457	143	174	365	207	161	8819	13842	923	563	94	296
1957	144	489	668	607	7885	3329	73943	84810	12684	1077	107	1908
1958	1262	2504	340	492	229	842	9599	5912	3191	0	1007	6265
1959	1844	320	197	340	1735	982	6458	1884	8574	11219	125	1271
1960	28755	392	746	351	169	165	5772	795	65	9604	323	303
1961	5084	14	265	406	186	89	21	19168	13440	29078	169	2367
1962	853	3932	268	244	175	568	234	34	9711	1132	296	48556
1963	857	286	392	275	347	162	2900	15360	3079	69	330	471
1964	45	1228	248	313	303	674	124	2900	1978	0	224	2343
1965	34	96	100	186	365	72	2112	39219	14321	660	1300	7809
1966	9773	488	152	255	175	364	29505	6989	6077	570	5642	4955
1967	595	182	237	279	643	595	206	96	33555	3464	1138	4229
1968	332	372	389	626	581	1631	2976	13737	1776	1075	87	731
1969	14	1804	341	253	393	515	4362	20741	2522	7	3770	2577
1970	1404	488	939	391	552	1190	482	180	555	8	7	1015
1971	261	103	175	214	155	96	771	8914	2014	2472	49277	11542
1972	2220	478	499	481	444	162	1078	5421	4478	1730	37142	20529
1973	3279	1587	743	1257	2907	10294	4383	1229	8760	2484	275	6519
1974	368	323	393	486	323	390	795	1457	722	0	2862	16333
1975	24110	1593	954	880	1794	676	674	25741	2785	9228	11101	4961
1976	829	1999	912	716	571	513	2193	1667	430	8845	400	6828
1977	3888	775	830	963	1362	2306	46985	36518	3149	164	2992	20440

TABLE 12

EVAPORATION DATA
COLORADO RIVER SYSTEM

Month	Net Lake Surface Evaporation Inches
October	4.92
November	4.08
December	2.40
January	2.40
February	2.76
March	4.32
April	4.68
May	4.32
June	7.20
July	8.52
August	9.72
September	7.08
TOTAL	62.40

TABLE 13

HYPOTHETICAL DEMAND PATTERN
COLORADO RIVER, TEXAS

Month	Demand* (cfs)
OCTOBER	30
NOVEMBER	30
DECEMBER	30
JANUARY	30
FEBRUARY	30
MARCH	30
APRIL	50
MAY	240
JUNE	420
JULY	500
AUGUST	500
SEPTEMBER	50

*Basic Demand Pattern - Values shown were adjusted in selected simulation studies.

TABLE 14 EFFECTS OF STORAGE DISTRIBUTION AMONG RESERVOIR

(NO GROUND-WATER USE)

AVG. DEMAND CFS	STORAGE OPERATION	EVAPORATION CFS	SPILL CFS	SHORTAGE CFS	SYSTEM STORAGE START AC-FT	END AC-FT	DIFF. CFS	NET YIELD CFS
1. RESERVOIRS AS CONSTRUCTED*								
88 (var.)	BALANCED	66	0	0	384,600	316,000	-3	85
99 (var.)	UPSTREAM RELEASE	55	0	0	384,600	318,700	-3	96
104 (var.)	3 EMPTY RES.	50	0	0	384,600	307,300	-4	100
2. RESERVOIRS REDUCED IN SIZE*								
91 (var.)	BALANCED	60	2	0				91
100 (var.)	UPSTREAM RELEASE	50	5	1				99
97 (var.)	3 EMPTY RES.	36	18	0				97

*RESERVOIR CAPACITIES (AC-FT)	J.B.THOMAS	COLORADO CITY	CHAMPION CR.	E.V.SPENCE
1. AS CONSTRUCTED	203,600	31,800	42,500	488,800
2. AS REDUCED FOR STUDY	82,200	31,800	42,500	195,000

TABLE 15

Effects of Conjunctive Use of Ground Water
(Balanced Reservoir Operation)

Avg Demand cfs	Ground-water operation	GW cfs	Shortage cfs	Eval cfs	4-Reservoir Storage Total			Net Yield cfs
					Start (ac-ft)	End(ac-ft)	Diff (cfs)	
105 (var)	60 cfs max	8	0	59	384,600	280,900	-5	92
97 (var)	8 cfs const	8	1	65	384,600	314,600	-3	85
121 (const)	60 cfs max	19	0	54	384,600	270,500	-5	97
105 (var)	19 cfs const	19	0	68	384,600	325,500	-3	83
105 (const)	19 cfs const	19	0	67	384,600	338,600	-2	84

TABLE 16

AREA AND CAPACITY DATA, PINE FLAT RESERVOIR

Elevation (ft msl)	Area (acres)	Capacity (acre-feet)
572	0	0
602	108	1,052
632	508	9,478
662	981	31,957
702	1,562	82,646
742	2,234	158,484
782	2,903	261,223
822	3,574	390,664
872	4,436	590,686
970	6,350	1,115,200

TABLE 17

OPERATION GUIDE FOR PINE FLAT RESERVOIR

Month	Conservation Capacity (ac-ft)	Flood Control Capacity (ac-ft)
October 31	880,000	121,000
November 30	650,000	351,000
December 31	525,000	476,000
January 31	525,000	476,000
February 28	650,000	351,000
March 31	805,000	196,000
April 30	910,000	91,000
May 31	975,000	26,000
June 30	975,000	26,000
July 31	990,000	11,000
August 31	1,001,000	0
September 30	1,001,000	0

TABLE 18

MONTHLY INFLOWS IN CFS-DAYS
PINE FLAT RESERVOIR

WATER YR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1900	10913	18973	31020	53440	20970	54400	65330	184830	159190	40050	11620	8095
1901	8455	41410	23315	118900	92890	92550	134020	316270	384420	192610	71250	14585
1902	15130	19850	19520	11900	17420	44260	119610	199130	235420	51230	18200	7260
1903	6260	11945	13790	28300	25540	45780	99360	279290	231230	60950	16930	7090
1904	6230	7020	6590	6305	18865	67710	106980	297590	217270	61920	32780	21555
1905	60075	19030	11385	14175	25595	58670	83370	184710	194500	58640	14275	6337
1906	5633	6102	8220	73490	34330	166430	144970	343270	507880	505740	136060	33900
1907	15795	11790	21675	44405	50830	125080	203080	283810	314230	229230	60690	16380
1908	13460	10955	15455	18305	22840	49765	91870	105270	77750	46300	33645	16995
1909	12880	9535	10195	101040	87320	63640	144250	305540	422600	189500	45280	19255
1910	12455	20530	54960	86770	37520	84880	176890	233940	114880	47906	15809	10343
1911	10329	9036	12836	79445	72110	135920	157410	260790	378680	240750	49535	19380
1912	14503	11983	10781	12092	11114	20850	37005	135680	171530	40520	15452	6743
1913	6974	7044	5191	7215	10630	19605	58370	148270	102750	52560	34256	21267
1914	7253	10237	11695	131007	55190	90800	129150	293150	300910	179490	56433	20410
1915	16545	10358	7761	12107	43408	50110	112270	195910	315440	117460	23147	11482
1916	6510	6300	11434	123943	85460	139560	226180	333850	366600	167130	47680	18149
1917	34768	19237	21068	21682	61015	46640	115770	201870	294510	98580	30120	8969
1918	6485	6330	6663	6563	11005	58970	97980	165760	251740	46933	13236	15669
1919	43368	16248	17723	12468	23957	39065	103500	231980	76170	27410	9261	5676
1920	7128	5920	13196	10168	12305	52312	82720	244700	197350	57033	17191	8074
1921	12948	16058	18273	25438	31351	67030	93140	196820	223960	65228	14852	8085
1922	7024	6110	28277	34686	45264	49290	82230	335320	355840	114130	35857	13292
1923	7206	11784	34204	28330	27740	40959	105010	252860	153710	87680	21006	13860
1924	11269	7799	5937	6978	8399	10481	43911	74870	15696	6532	3257	2281
1925	3876	10499	14460	13975	31227	43030	96760	199840	147460	60203	22307	6495

TABLE 18 (Continued)

WATER YR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1926	8999	7166	9004	6036	20027	33897	150190	190140	69370	18652	6464	3463
1927	3834	30439	22446	20009	80000	65580	121120	268250	257780	98370	23473	9480
1928	8317	32640	15135	14658	16289	50885	80790	163520	76870	19582	7546	3696
1929	3900	5746	7703	7667	10572	28939	49900	166710	100290	31694	9548	5604
1930	3632	3375	4170	7573	15945	36211	86200	116410	121400	27733	8311	3830
1931	4334	5959	4519	6349	8813	15577	49511	93060	29584	7205	5110	5074
1932	3389	4302	31227	29371	81570	64670	114960	258790	299750	125760	27662	8660
1933	7901	5054	5693	13730	15000	32894	79810	117310	230980	68428	14083	5202
1934	4217	5453	19041	20759	18555	49328	88950	71770	31702	12674	5743	3724
1935	3357	8144	12416	24079	31273	41782	150160	228430	235900	58804	16042	7013
1936	6791	7099	6929	13882	91009	68170	174890	287670	182600	75150	24355	7504
1937	7188	7447	20494	19827	133753	90930	138360	376180	267080	90740	20355	7843
1938	6102	6360	87935	27652	85910	188420	177610	353860	433620	202560	59500	21391
1939	21688	17468	14015	16392	22495	47096	121790	121700	63710	23691	14233	6920
1940	12783	6286	5760	49456	66033	85470	134440	288620	188440	46647	12734	5951
1941	7665	7698	35229	41978	81310	86310	102030	347480	341220	172360	45953	12748
1942	9273	12900	31858	43042	35873	55419	120230	226860	311350	124560	30102	9545
1943	6629	14327	17161	76699	48070	131380	159400	279930	170340	86430	23409	7982
1944	6889	6479	7857	11145	23150	46186	59680	201400	144520	61649	13848	6103
1945	5636	20671	19980	16553	100910	62510	127830	252750	267270	117260	35350	13093
1946	31789	32183	43799	33808	23707	55770	148500	235660	134000	50604	15839	7086
1947	13583	31864	40664	23337	26501	42671	85700	186150	73480	20908	8160	5268
1948	8010	8233	6517	5998	7227	15476	69410	188660	143740	36097	8428	4077
1949	3974	3944	5233	6700	9794	26995	98006	186050	106810	23066	9075	4680
1950	4147	8022	7679	16393	37367	38065	140940	196580	140790	40100	9359	6375
1951	7059	113354	111540	41661	36583	49967	96450	160480	128640	44830	11351	5211

TABLE 19

EVAPORATION DATA
PINE FLAT RESERVOIR

Month	Lake Surfaces Net Evaporation (inches)
October	3.99
November	.70
December	-2.16
January	-2.39
February	-2.01
March	-.46
April	1.87
May	4.84
June	7.15
July	9.30
August	9.05
September	7.07
TOTAL	37.95

TABLE 20

SEASONAL VARIATION OF DEMANDS AT PINE FLAT RESERVOIR

MONTH	DEMAND IN PERCENT
OCT	6.9
NOV	1.9
DEC	0.9
JAN	1.1
FEB	3.2
MAR	6.4
APR	10.1
MAY	13.3
JUN	15.7
JUL	17.2
AUG	16.3
SEP	7.0

TABLE 21

Results of Case Study
Pine Flat Reservoir

Stor. Cap. (ac-ft)	Demand (cfs)	Evap. (cfs)	Shortage (cfs)	Spill (cfs)	Net Yield (cfs)
1,001,000	1,132 (Var.)	23	0	957	1,132
1,001,000	1,136 (Const.)	24	0	949	1,136
1,001,000	1,300 "	23	16	803	1,284
1,001,000	1,500 "	22	43	633	1,457
1,001,000	1,800 "	20	124	424	1,676
1,001,000	2,433/1,022	20	650/0	318	1,783/1,022
2,000,000	1,500 (Const.)	36	1	551	1,499
4,000,000	1,750 "	56	1	255	1,749
6,000,000	1,935 "	66	1	59	1,934
6,000,000	2,025 "	59	30	31	1,995
6,000,000	2,100 "	54	55	8	2,045
6,000,000	2,200 "	44	113	0	2,087
1,001,000	993 (Var.)	219*	0	902	993

*Using Sam Rayburn Area - Capacity Relation

TABLE 22

AREA AND CAPACITY DATA, SAM RAYBURN RESERVOIR

Elevation (ft msl)	Area (acres)	Capacity (ac-ft)
0	0	0
96	1,000	10,000
102	2,100	17,000
112	10,000	30,000
120	18,300	180,000
130	34,000	450,000
140	54,000	900,000
150	78,000	1,448,000
165	116,000	2,900,000
183	180,000	5,610,000

TABLE 23

MONTHLY INFLOWS IN CFS-DAYS
SAM RAYBURN RESERVOIR

WATER YR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1929	2678	11785	43831	93990	109470	146250	68680	299210	293978	32489	5013	4719
1930	1751	46816	60578	199400	218350	126040	52874	88985	71655	6582	2654	3511
1931	33923	29192	156870	168810	152550	157510	82610	119805	12779	6656	5689	2812
1932	1388	11188	168065	509870	566510	349100	102970	45410	12698	7607	5346	3663
1933	2857	3664	33277	106770	153640	208590	174840	122240	53634	101274	72515	16336
1934	6287	5360	16746	199350	211510	324590	213880	60708	13330	4757	2483	1997
1935	2707	16830	105910	127210	94530	100458	93670	566000	129900	25224	7786	6168
1936	4808	33238	163540	47540	48080	45673	18406	38972	18657	63192	12717	3638
1937	2993	4249	29689	232860	137050	131070	105840	20562	12987	4311	2946	4084
1938	9229	10734	68720	139910	103580	124000	363370	83420	24745	20158	19706	4183
1939	2774	10243	14190	117941	198630	150730	50830	34300	32034	4688	2943	1566
1940	2000	4725	99261	97550	253050	64230	100170	90907	77610	25470	16906	22979
1941	4867	164484	585700	328640	178670	289220	105790	178210	164110	66700	21511	20959
1942	63580	355240	171660	131220	98950	143690	205070	149820	108030	37681	68913	44250
1943	13053	18828	23191	82170	47580	41740	32702	19196	14495	8416	4299	2874
1944	4227	9060	14032	122920	172100	211300	200860	780000	203816	11749	6592	22937
1945	6421	25108	164610	443240	268100	239870	411800	111240	39028	94660	34320	9814
1946	83547	42850	89820	346910	446450	286900	174310	187090	198540	47403	16986	29949
1947	22741	196577	167050	367970	139340	271500	161880	154080	101030	19257	6888	5281
1948	5779	25186	75399	70030	234100	156680	135170	75670	23081	9112	2973	3084
1949	2723	16561	22443	102067	143520	176290	156330	77650	40869	17099	14189	8948
1950	86809	50300	138728	383030	327830	187970	69120	236800	316960	36556	12201	14085

TABLE 24

EVAPORATION DATA
SAM RAYBURN RESERVOIR

Month	Net Lake Surface Evaporation
	(inches)
October	2.04
November	-.54
December	-1.36
January	-1.44
February	-1.32
March	-.12
April	-.72
May	-.24
June	1.20
July	2.40
August	3.36
September	2.04
TOTAL	5.30

TABLE 25

Results of Case Study
Sam Rayburn Reservoir

Demand (cfs)	Evap. (cfs)	Power (mw-hr/yr)	Spill (cfs)	Shortage (cfs)	Net Yield (cfs)
2,445	78	107,100	669	1	2,444
3,000/ 2,270	75	105,800	402	276/0	2,724/ 2,270

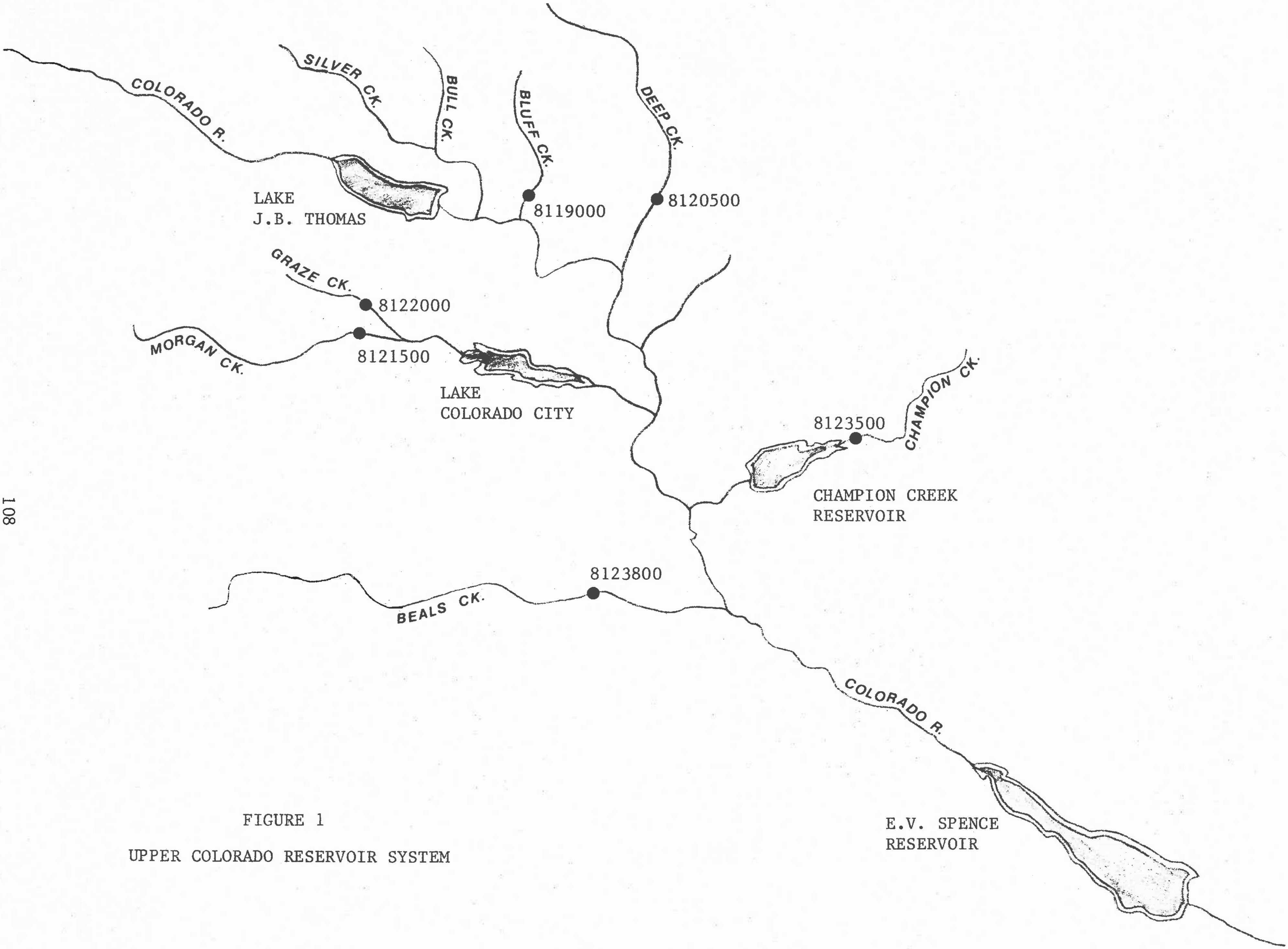
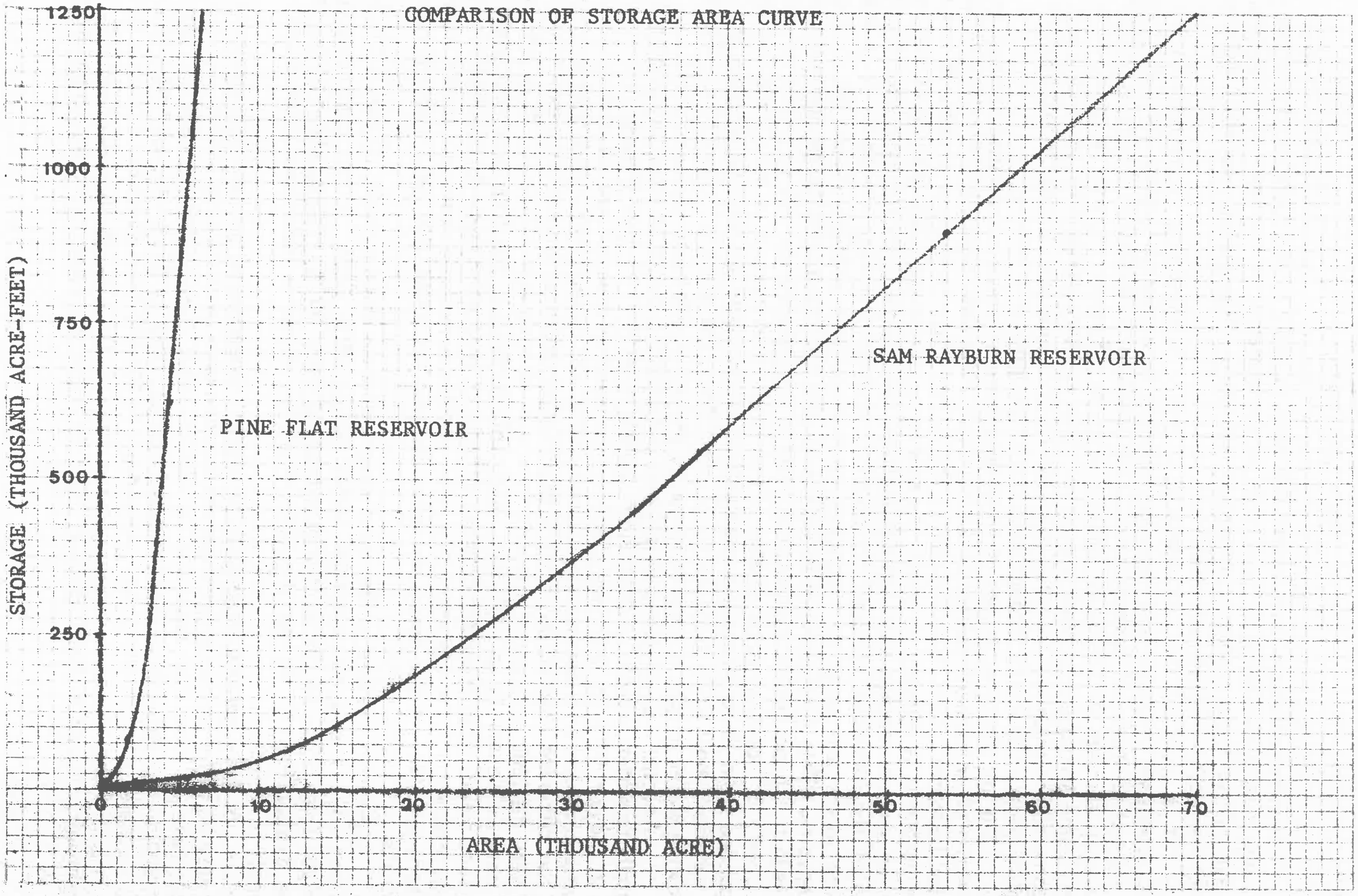


FIGURE 1

UPPER COLORADO RESERVOIR SYSTEM

FIGURE 2

COMPARISON OF STORAGE AREA CURVE



PART 3 - DISCUSSION AND CONCLUSIONS

CHAPTER I
DISCUSSION

Studies described herein were designed to apply to complete reservoir systems. Although case studies were derived from partial systems for the sake of simplicity and manageability, they represent complete systems. Results of studying incomplete systems as such would be inconclusive.

It is apparent that conservation of water (maximizing its availability for the most effective use) can best be accomplished in a closed system through storage. During initial stages of development, great gains in conservation can be accomplished ordinarily through provision of surface storage. Surface storage is most effective where time variations in flow are large. This is characteristic of semi-arid and arid regions, where evaporation rates are also high. Generally, losses in evaporation are small compared to losses through spill due to inadequacy of storage.

During the later stages of river development where substantial storage exists, provision of additional storage is decreasingly effective, because the critical drought period becomes longer, which subjects the stored water to longer periods of evaporation before it is released or used. As this stage approaches, integration of the operation of surface storage with aquifer storage can substantially improve the effectiveness of the increased storage. In essence, long-term storage should be in an aquifer where losses are small or negligible, and short-term storage should be in surface reservoirs. This is illustrated in Tables 14 and 15. By adding three upstream reservoirs in this hypothetical system, the yield is decreased from 100 to 85 cfs in addition to a zero or constant groundwater withdrawal. However, if a well field capacity is expanded from 19 to 60 cfs and used only when droughts are well under way, the yield of surface runoff rises from 84 to 97 cfs. Thus, the yield is raised 13 cfs simply by allowing water to stay underground during periods of adequate surface runoff.

Another way of conserving water during later stages of river development is to distribute water, insofar as is feasible, among reservoirs so that storage is concentrated in those reservoirs that have the least increase in area per unit of storage increase, giving consideration also to any differences in net evaporation rates that might exist at the different reservoirs. From a practical or political (social) standpoint, this may be very difficult because of the multiple uses of reservoir facilities. It is interesting to note in Tables 14 and 15 that, using this technique, the four-reservoir yield from surface runoff rises from 85 cfs when storage is proportionately distributed among the four reservoirs to 96 cfs when it is kept in the downstream reservoir to the maximum extent possible. If the upstream reservoirs did not exist, the yield would increase to 100 cfs.

Another feature of the later stages of river development, illustrated in Tables 14 and 15, is the high evaporation losses compared to yield. In this case, evaporation ranges from 55 to 66 cfs for yields averaging about 90 cfs. Thus, about 40 percent of the available water is sacrificed in order to obtain a maximum dependable water supply in this case.

A very general appraisal of water conservation factors in relation to the degree of water resource development can be made by reviewing Tables 14, 21 and 25. The case of Pine Flat reservoir is that of least storage development in relation to potential development. The average runoff used is 2118 cfs, and the maximum dependable yield for the existing reservoir (1,001,000 acre-feet) is 1132 cfs. Evaporation losses are trivial in relation to the spill of 957 cfs. With a 6,000,000 acre-foot reservoir, the yield could become 1934 cfs while the losses remain nominal at 66 cfs.

Sam Rayburn Reservoir, on the other hand, represents a moderately high degree of development. A yield of 2444 cfs is obtainable, compared to an average inflow of 3245. Because of the humid climate, evaporation losses are a low 78 cfs. Spill is very substantial at 669 cfs, indicating that further conservation can be obtained through provision of more storage. The four-reservoir Colorado River system represents full development. A yield of 85 cfs is obtained from an average runoff of 151 cfs. The difference is lost through evaporation, which is largely due to the arid climate and the necessity to use broad valleys for relatively shallow reservoirs. Further conservation potential through reservoir construction and management is relatively small.

While variable demand patterns depending on water availability have been studied, they are generally of interest only during intermediate stages of development. In municipal and industrial uses, as well as in hydropower generation, water is of high value and is effectively useful only insofar as its supply is dependable. Even in agriculture, the dependability factor is becoming more important as large investments in farmland development and high-yield crops can be hurt seriously by water shortages. More and more is supplementary water of little value and shortage a great cost. The response function for water-related investments then has a sharp break at the point of dependable yield. It is this condition that must be considered in assessing conservation accomplishments. If the firm yield of a system is increased, water is conserved. If it is decreased, water is wasted. Of course, this applies to a complete system including water needs in estuaries.

CHAPTER
CONCLUSIONS

Studies described herein demonstrate the following:

1. Conservation of water must be associated with greater utilization and not simply reduced losses of any type or types.

2. In the early stages of regional water development, surface storage is a highly effective means of conserving water for effective use.

3. As regional water resources become highly developed, underground storage in aquifers, using natural replenishment and controlled withdrawal, can substantially reduce losses and increase the utility of water resources.

4. In dry regions, losses to evaporation from long-term carry-over by surface reservoirs can be a high percentage of the usable firm yield.

5. In humid regions, evaporation losses are generally of minor or even trivial significance.

6. Where a low degree of reservoir regulation exists, a 2-stage demand can be very useful, where only priority uses are served during low reservoir stages. With a high degree of regulation and generally in humid regions, little, if any, gain is made by supplying supplementary water at high reservoir stages at the expense of reducing the firm yield at lower stages.

7. Substantial water savings can be effected, especially in dry regions, by distributing the water among reservoirs in a system so as to reduce over-all evaporation losses, where feasible.

8. In dry regions, losses can be greatly reduced by using deep reservoirs instead of shallow reservoirs.

9. With a fixed amount of storage, water yield and utilization can be greatly increased simply by delivering water at a higher rate until the supply is exhaused. For some uses, such as irrigation, this can produce more benefits than losses over the long term.

10. For a given reservoir, as the yield or usage of water increases, power generation is first increased because of reduction in spill, and then decreased because of maintenance of lower reservoir contents and consequently lower heads.