Optimum Operation of Desalting Plants as a Supplemental Source of Safe Yield

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Optimum Operation of Desalting Plants as a Supplemental Source of Safe Yield

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FOREWORD

This is one of a continuing series of reports designed to present accounts of progress in saline water conversion and the economics of its application. Such data are expected to contribute to the long-range development of economical processes applicable to low-cost demineralization of sea and other saline water.

Except for minor editing, the data herein are as contained in a report submitted by the contractor. The data and conclusions given in the report are essentially those of the contractor and are not necessarily endorsed by the Department of the Interior.

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Dean F. Peterson, Jr., first suggested that this study be made. His interest in the conjunctive operation of desalting plants with existing water systems grew out of his participation in a study of the recent drought in the northeastern states. Without his initiative, ideas, leadership, and lucid criticism the project would neither have been initiated nor have reached its goals.

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INTRODUCTION AND OBJECTIVES

In recent years, population and economic growth have impinged with mounting pressure on natural water supplies. Water shortages occur in the humid east as well as in the arid west because natural supplies are already in use or are too expensive to develop. These shortages are aggrevated and dramatized by periodic droughts, such as the one occurring in the northeastern United States during the mid-1960's which resulted in drastic curtailment of supplies in some of the large northeastern cities. The problem is not only drought but basic firm supply.

Development of natural surface water supplies becomes increasingly expensive. Indeed, the difficulty of mounting cost is not the only problem. Reservoir sites are more difficult to obtain; more and more frequently they contain resources of increasing historic, scientific, or aesthetic value. As a result, there is a growing uneasiness, if not outright opposition, about aesthetic and ecological consequences of large-scale water development. Nevertheless, critical needs for fresh water continue to climb rapidly. Desalting water from the seas or from brackish supplies, using expected new sources of inexpensive energy, holds the promise for helping to meet these needs. Desalting technology is developing at a rapid pace. Both distillation and membrane desalting plants of greater capacities are being built to meet a wide variety of water requirements. The technology to build large capacity plants of 50 MGD and over is now in hand. But if the promise is to be realized, a basis must be found for comparing, in common terms, the effectiveness of desalting plants with alternatives of constructing reservoirs, making large-scale transfers, or pumping from groundwater.

Two considerations have prompted this study. First, existing water systems are usually based on natural supplies which are highly variable over a period of time. If a desalting plant is utilized to supplement the supply of an existing water system, it is quite clear that it should not be operated during the periods when natural water yields with an incremental cost of essentially zero are adequate to meet demands. For this type of operation the desalting plant will perform a peaking function; i.e., it will fill in the shortages of nature rather than run continuously.

The second consideration relates to the purpose of the municipal water system or the water district in making an additional investment in a supplemental supply service. Usually the water utility must be able to provide a certain rate of flow on demand. The capacity of the water system from the point of view of the utility owner, is the rate of flow the system can deliver rather than the total quantity of water. Like an electrical utility, what is purchased by additional investment is the capability to produce more megawatts of electrical flow and not total kilowatt hours.[1] What the water utility buys then, is an assured new (firm) yield rate. In comparing desalting with other alternatives, the relevant parameter to compare is the unit annual cost of additional firm yield.

The concept of firm yield has many interesting ramifications. If there is no storage on a stream, the only yield that can be assured at all times is the minimum flow of the stream. But even this yield can be described on a probabilistic basis. For example, in one year out of ten on a particular stream, flow may drop below 100 MGD; below 75 MGD one year in 50, and below 70 MGD one year in 100. To define the firm yield, then, there is an associated probability level which must be specified, because the greater the reliability required, the less the firm yield.

A logical first step in firming-up the yield of a natural supply is to store waters in reservoirs during periods of high flow and release them during periods of low flow. The increase in firm yield can be calculated by making a reservoir operations study. Such a study involves accounting for the probable inflows and outflows day by day or month by month; i.e., solve the equation of continuity. When a draft on the system is reached such that the reservoirs just avoid running dry, the draft is the new firm yield. The level of reliability depends on the sequence of years examined. In other words the firm yield depends on the particular sequence of hydrological events used in the reservoir analysis. Ordinarily, historical hydrographic records are quite short. Records exceeding 50 years are more the exception than the rule. Furthermore, future events will almost certainly be different and in a different sequence than those of the past. However, by using computers and modern operational hydrology,[2] hypothetical sequences of hydrological events of any length desired, which have the same probabilities of occurrence as those of the past, can be generated. Using such series the analyst may extend records and perform

[1] The view of the utility management may be different from that of individual customers who pay for gallons or kilowatt hours. Even so, larger electrical consumers usually pay a ***demand*** charge; i.e., a charge which permits the kilowatt hours to be drawn at a certain rate. For the utility, though, the time dimension implied in a rate of flow cannot be ignored.

[2] Operational hydrology refers to the theory of synthetic generation of sequences of hydrologic events.

the reservoir operations analysis for any specified period. This procedure permits estimation of firm yield reliability to any significance level desired; i.e., to the degree to which the record of the past is a fair sample of the future.

Adding a desalting plant to a surface supply system, including reservoirs, adds a further complication to the problem of firm yield analysis. Such a plant usually does not add a firm yield equal to plant capacity because future events determine the optimum time to turn the plant on and off. Since these times cannot be known in advance, there is always some spillage of water. The operator must make a judgment about turning the plant on soon enough that the reservoir does not run dry in the future and turning it off early enough that the water is not wasted over the spillway. If the costs of firm yield added by desalting plants are to be compared with those from other sources, then means must be found to predict the *amount* a desalting plant will add to the firm yield of a water system and at *what cost*. The research reported herein deals with these topics and describes a computer program (hereafter called the Operating Rule Program) which can be used to plan optimal combinations of desalting plant sizes with conventional water supply systems.

Past studies of the use of desalting plants as a means for supplementing natural supplies usually have assumed base load plant operation for the desalting plant. Two notable exceptions to the base load assumption are as follows.

A preliminary study of conjunctive operation of a 200 MGD plant for New York City was made as part of a study by the Northwest Desalting team in 1965 and reported by the Office of Saline Water (1966). The study showed that the desalting plant would be operated only 70 percent of the time while supplying the required firm yield during a drought period. This load factor falls within the range of load factors reported in the case studies of this report.

Mawer and Burley (1968) reported that "a desalination plant can be operated in conjunction with a conventional reservoir to give increased yields at costs as low as 50 percent of the equivalent base-load desalination cost." Their claim is supported by the present study.

In this study a digital computer program is developed for applying modern operational hydrology to determine the firm yield that will be added by a desalting plant and the associated cost of the firm yield. The principal problem concerns the plant operating rule; i.e., when to turn the plant on and off. Improper decisions either waste desalted water or fail to utilize the plant to prevent shortages. Since all possible decisions cannot be studied efficiently, the computer program screens the possible operating rules and eliminates those that cannot produce the required water or those that inefficiently produce too much. The remaining rules are then utilized in a cost subroutine that determines the cost of producing the added firm yield. The near optimum rule can then be selected.

The program is visualized as a planning tool. Its purpose is to provide information on the probable value of a desalting plant as a possible alternative for adding yield to a water system. This alternative may then be compared with other alternatives in common terms. While the program will certainly provide guidance for actual operation once a plant is installed, this is not its primary purpose. A skilled operator should do even better because he will have more information at any given time. The writers believe, however, that the program closely predicts the best that can be expected under real-life conditions.

Demonstration of the computer program using real planning situations is important and this has been done for three case studies.

The specific objectives of the research are stated briefly as follows:

1. To develop a digital computer program that can conveniently determine the optimum operating rule for conjunctive operation of a desalting plant in order to help assess alternatives and to aid in decision making concerning plant design.

2. To apply the Operating Rule Program to three real-life situations where a desalting plant can be operated in conjunction with a reservoir and water system.

3. To assess the impact of conjunctive operation on the performance characteristics and the design of a desalting plant used in intermittent service and to identify the unique features of such plants.

Using generated hydrologic sequences as an input, the central problem which the computer program must solve is the determination of the correct operating rule considering other inputs of demand and cost. Once the correct operating rule is determined, the unit cost of new firm yield is known. Furthermore, a repeated series of computations, each with a different plant size, leads to a choice of a near optimum plant capacity. Similarly, the best reservoir size can be investigated.

SUMMARY

The Operating Rule Program receives central focus in this report. It is written in Fortran IV computer language and consists of about 1,700 statements. One of the unique features of the program is its general format and easy applicability to a wide variety of conditions.

In general the Operating Rule Program goes through the following steps to find the optimum rule: The historical hydrologic data for the reservoir and the water system are first analyzed. Long hypothetical streamflow sequences are then generated having the same statistical characteristics as the known hydrologic record. Using the generated hydrographs along with the given reservoir characteristics and an assumed desalting plant capacity, the operation of the desalting plant is simulated by the computer program to test the ability of the various proposed operating rules to meet the needed water demand. Decisions as to when to turn the plant on and when to turn it off are determined by the operating rule. Parameters affecting the operating rule are the reservoir storage contents and the season of the year. All rules that can produce the needed additional firm water yield are feasible operating rules. Each feasible rule is evaluated by simulating operation of the system over an arbitrary period of time equal to some multiple of the economic life of the desalting plant and by determining the unit cost of the added firm yield. Several such simulation computations are conducted with different hydrologic sequences to determine the mean cost for each rule. The operating rule that produces the water at least mean annual cost is the relevant one, and the associated added firm yield and its unit cost are the desired outputs.

To demonstrate the usefulness of the Operating Rule Program, three real water systems were studied after adapting the data to the format required by the computer. These systems are the Cachuma Project near Santa Barbara, California; the Deer Creek Project near Salt Lake City, Utah; and the New York City water supply system. Each system used in the applications has features different from the others. The Cachuma project involves a single stream and reservoir in an arid environment. The Salt Lake City system illustrates a way of analyzing part of a system consisting of several streams and reservoirs in a semi-arid area in which the water supply originates in nearby high mountains. The New York City system example analyzes a large complex system by lumping all storage and watershed inflows into one composite reservoir and one inflow. This system is located in an area of relatively high rainfall (approximately 40 inches per year).

Sensitivity of the optimum operating rule and the associated costs to changes in various input parameters are described and the influence of intermittent conjunctive operation on the plant design and plant operating features is discussed. Finally, additional useful research opportunities are pointed out.

The analyses of each of the systems were based on minimum input data but were sufficient to demonstrate the operability and applicability of the computer program. The results shown should be considered only illustrative of the range of values to be expected under the assumptions made. Principal results of the application of the program are summarized in Table 1 for the three systems analyzed.

The computer program developed under this contract is potentially a practical tool useful to water resources planners in helping to assess the role of desalting plants operating in conjunction with existing water supply systems. The program, as applied to specific cases, will provide data not only on the optimum operating rule for the desalting plant, but also will provide useful engineering information relative to design requirements of a desalting plant operated in a conjunctive mode to increase firm yield of a system.

Table 1. Summary of results of the application studies.

Name of application project	Probability level defining firm yield %	Demand MGD	Firm yield without desalting MGD	Optimum plant size MGD	Optimum operating rule (reservoir fraction full) ON	OFF	Average plant load factor %	Desalted water use/production ratio (efficiency)	Minimum cost[a] in $/yr. per MGD of added firm yield
Cachuma	95	80.0	24.2	75	0.36	0.40	65	0.82	197,500
Salt Lake-Deer Cr.	99	220.0	176.8	65	.46	.80	59	.75	183,400
N. Y. City system	99	1970.0	1759.6	250	.77	.70	51	.24	145,200
N. Y. City system	95	1970.0	1856.2	150	.80	.57	57	.30	164,200

Assumptions for the computations:

Five simulation periods of 30 years each
Five firm yield periods of 75 years each
MSF, single purpose desalting plant
30 years plant life
Interest rate 4 5/8% (Fixed charge rate = 7.23%)
Fuel cost = 35c/MBTU

[a]Average levelized annual cost for the five simulation periods.

DEVELOPMENT OF THE OPERATING RULE PROGRAM

General Approach

The methodology described herein combines simulation and operational hydrology through the use of a digital computer to find the least-cost alternative for meeting an increased water demand with a desalting plant operated with an existing water system. According to Hufschmidt and Fiering (1966), simulation, with the advance in computer technology, has become a valid planning tool in the water resources area. Operational hydrology services the simulation by providing sequences of "equally likely" streamflows.

Before a natural phenomenon can be simulated it is necessary to describe the various components of the system by mathematical models which have the response of the natural components. Upon adequate modeling of the system, the response to a number of inputs and constraints can be determined in rapid succession by having a computer carry out the computation required by the mathematical models. By examining the various responses, the one which best meets the objective can be selected. The problem does not lend itself easily to an elegant analytical formulation, and to minimize study time in developing a practical means of determining the optimum operating rule, a computerized simulation approach was utilized.

General Description of the Simulation Model

Given a reservoir, a desalting plant, a postulated demand, and a sequence of likely future streamflows, the basic equation to be solved by the model is the equation of continuity; i.e., $H + (C)(J) - D - M = \Delta S$ in which H is the streamflow into the reservoir, C is the capacity of the desalting plant, J is either 1.0 or zero depending on whether or not the desalting plant is operating, ΔS is the change in reservoir storage, D is the demand, and M is other mandatory releases. This equation is solved month by month for a prestated demand over a time sequence. A separate solution of the continuity equation is made for each month; these solutions are tied together in time by the carryover storage S, which is carried forward from month to month. The 100 percent firm yield is defined as the demand D which can be met at all times without running short of water but also just emptying the reservoir. If the reservoir is emptied; i.e., S equals zero, in 5 percent of the years for a particular demand D, then the firm yield with 95 percent reliability equals that demand D. The period of examination can be made as long as necessary to obtain the level of reliability desired for any specified demand.

The computer must search through time to find that demand which is associated with the prescribed level of certainty; trial levels of demand are proposed and the computer calculates their probabilities. Based on these probabilities the search rapidly closes on the desired value of demand.

Intermittent operation of the desalting plant greatly expands the problem. If the plant is off at the beginning of any month, the decision has to be made whether or not to turn it on; if the plant is on, then the program must decide whether or not to turn it off. Assuming that on the average just one turn-on and one subsequent turn-off decision has to be made each year, the total number of monthly decision combinations in a 150-year period of operational hydrology would be about 4×10^{157}. Clearly some means for screening out most of these combinations is necessary.

An operator would not likely start the plant if the reservoir were full or nearly so, nor would he turn the plant off if the reservoir were nearly empty. Thus, reservoir storage is a good index for making an initial screening of turn-off and turn-on decisions. With the desalting plant off, the operator can decide that J remains zero if the reservoir contains more than A; and, with the desalting plant on, J remains 1.0 if the reservoir contains less than B. For a prechosen value of desalting plant capacity, C, several values of B are selected and the computer program finds the corresponding values of A which are just able to produce the required yield. Infeasible operating rules (rules that cannot produce the desired demand) and inefficient rules (rules that produce too much water) quickly can be screened out. Fig. 1 illustrates the process in graphical terms. The family of constant cost lines (if they were known) would show operating points (A,B) which could produce the required yield (or more) at the annual cost represented by the line. The set of points (A,B), with B preselected and A determined by the program to produce exactly the required yield, defines a feasible operating rule curve. Points below this curve cannot produce enough water while points above the curve produce more than is necessary and are thus inefficient. Once the less promising or infeasible rules are screened out, the computer program calculates the cost of producing the required yield based on unit cost data for capital and operating costs. The estimate of the minimum value of the cost function can then be refined by interpolating along the feasible operating rule curve. Graphically, the objective is to find the point of intersection of the feasible rule curve with the smallest value of cost at point X in Fig. 1. This triple

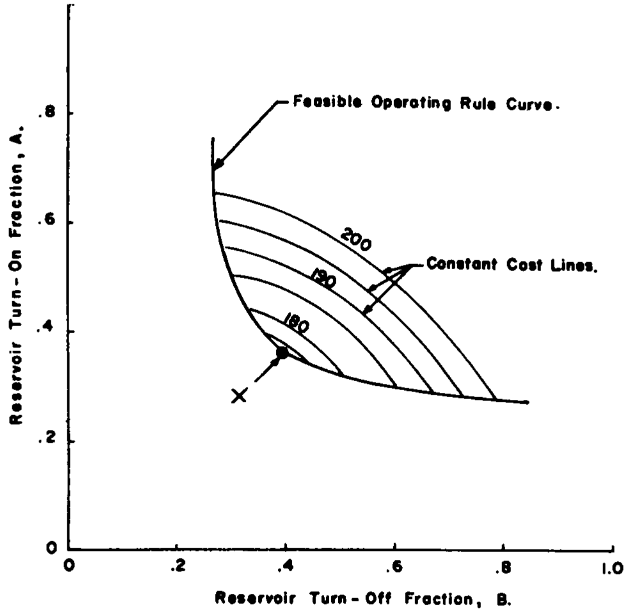

Figure 1. Objective function surface for fixed plant size.

intersection point specifies the operating rule and the minimum cost of producing the additional firm yield.

A prescribed demand can be satisfied by more than one size desalting plant; thus it is necessary to repeat the analysis for several plant sizes. The eventual result is to estimate the optimum size plant and its capital and operating costs to produce a new increment of firm yield, at the same time defining the plant operating rule.

Some refinement in the operating rule may be profitable depending on the season. One would normally be willing to permit the reservoir to draw down to a lower level if the subsequent months normally constituted the wet season of the year. Furthermore, the operating rule is not necessarily the way the plant will actually be operated in any given year once it has been constructed. The operator may have better real-time information on which to base his decision than the statistical history of the past available to the planner. The purpose of the rule is to greatly reduce the number of alternative cases that have to be investigated, and to rapidly determine the rule for maximum efficiency of operation. One could expect that the efficiency achieved in actual operation would not greatly differ from the best prediction using the operating rule, but could be better if good forecast information is available.

Simulation Model Data

The essential data for of the simulation model used in this study are:

1. Streamflow (inflow to reservoir),
2. Storage (reservoir) characteristics,
3. Draft on storage
   (a) Demand to be satisfied,
   (b) Mandatory release,
   (c) Losses, and
4. Desalting plant of specified capacity with the associated operating and capital cost data.

Units of inflow may be in either cubic feet per second (cfs) or million gallons per day (MGD) while storage may be given in acre feet (A.F.) or billion gallons (BG). A brief discussion of each item will serve to elucidate the overall methodology used in the computer program.

Streamflow

Streamflow representation in the simulation model is provided by means of operational hydrology. Operational hydrology, as described by Fiering (1967), involves the generation of equally likely streamflow sequences. The method is based on the fact that flows at stream gaging stations comprise a sample from a time series. A time series can be represented by a function of the form

$$q_t = f(t) + u_t \quad \ldots\ldots\ldots \quad (1)$$

in which

q_t is the value of the parameter at time, t
$f(t)$ is a deterministic component, and
u_t is a random component.

The extension of this type of function to a workable flow generator is reported by Fiering (1967) and the theory of streamflow generation will not be pursued any further in this report.

The streamflow sequences used by the simulation model are generated by subprogram GNFLO. This subprogram is a modified version of a computer program developed by the Hydrologic Engineering Center (1967) of the Corps of Engineers. Subprogram GNFLO, as now constituted will simultaneously generate monthly flows for as many as five gaging stations for periods up to one hundred years in length.

Operational hydrology should not, and indeed cannot be used indiscriminately. Fiering (1967) indicates that it cannot be used reliably on streams whose watersheds have been or will be altered appreciably with time by the activities of man or the forces of nature. Streamflow synthesis cannot improve the quality of a hydrologic record and is not a forecasting mechanism. It is, however, a means of obtaining a number of streamflow sequences of whatever length desired with certain statistical parameters identical to those of the historical record. The justification for generating a number of equally likely sequences is that this procedure removes the reliance of the analysis on a single, short sequence of streamflow and also permits estimates of the probability of a particular level of output.

The adequacy of the operational hydrology subprogram GNFLO is more completely discussed in Appendix B, "Evaluation of the Adequacy of Streamflow Operational Hydrology."

Storage characteristics

The reservoir storage capacity is assumed to be the same for each set of simulation computations on the computer. This assumption is reasonable since the program is applied to existing systems planning to supplement the natural supply with desalted water. Admittedly, a model that treats storage capacity as a variable would be useful in some planning situations, but is not necessary for those planners dealing with existing water supply systems, whose storage cannot be increased.

The program can be used to assess the effect of increased storage capacity on the cost of the supplemental water simply by making several sets of computations, each with a different reservoir size. The larger reservoir would produce more firm yield without desalting, and would also lead to more efficient conjunctive operation of the desalting plant with a corresponding lower cost. The savings in the desalting cost of meeting the demand could then be compared with the cost of providing the increased storage capacity.

The present Operating Rule Program could be modified to search automatically for the optimum reservoir size. The reservoir cost vs. size would be required as an input. Unfortunately, the length and complexity of the program would substantially increase. Effort to develop this modification is suggested as a worthwhile goal for future research.

In the simulation model the reservoir storage is assumed to meet a primary demand that can be described by a yearly total demand and a set of monthly demand coefficients. This primary demand may be for irrigation, for municipal and industrial water needs, or for other uses so long as the monthly coefficients describe the total demand pattern. An extension of the model would be required if the reservoir is to fulfill other multiple purposes that follow a different demand pattern.

The limits of a conservation pool that can be drawn on when demand is greater than the seasonal supply and replenished when the condition is reversed must be defined. The parameters required to describe the storage in the simulation program are the maximum available capacity of the reservoir, the dead or inactive storage, and elevation-capacity-surface area curves in tabular form.

Draft on storage

Draft is defined as outflow from the conservation pool to satisfy demands of the following types:

(a) Releases to meet the projected demand,
(b) Mandatory releases for other purposes, and
(c) Evaporation losses.

Projected or target demand is furnished by the program user. By utilizing such information as per capita consumption of water and population projections, the planner can estimate future water requirements. This demand rate in million gallons per day (MGD) represents an average rate over the period of a year. Along with the overall demand rate, the planner must furnish a set of monthly coefficients which are the ratios of the monthly demands to the average monthly demand. Thus,

$$r_i = \bar{R}\, C_i \text{ for } i = 1, 2, \ldots, 12 \quad \ldots (2)$$

$$\text{subject to } \frac{1}{12} \sum_{i=1}^{12} C_i = 1$$

in which

r_i is the monthly demand rate,
$\bar{R}$ is the average of the monthly demand rates, and
C_i is the monthly demand coefficient.

If the inflow is on a water year basis, $i = 1$ represents October, and if on a calendar year basis, $i = 1$ represents January. The monthly rates are converted to volumes on the basis of the number of days in the given month.

Mandatory releases from storage generally have priority over all other uses. Usually, the mandatory release must satisfy the terms of some decree or compact. An example would be that of maintaining a certain gage height at some downstream point for the purpose of conserving fish and wildlife and/or water quality. These releases are described in the same manner as the target demand; that is, an average rate of release in MGD over the period of a year is specified along with release coefficients for each month. If the releases are uniform for each month, then all C_i's would equal 1.0.

Evaporation losses are represented in the model by monthly evaporation coefficients. The coefficients are in the form of average evaporation in inches per month. The water surface area in acres must be known. Then, the monthly volume of water in billions of gallons (BG) lost by evaporation is obtained from

$$E_i = 2.7152 \times 10^{-5}\, \bar{A}_i e_i$$

$$\text{for } i = 1, 2, \ldots, 12 \quad \ldots (3)$$

in which

E_i is the volume of water (BG) evaporated in month i,
$\bar{A}_i$ is the average water surface area (acres) in month i, and
e_i is the evaporation coefficient for month i.

the water surface area is given in the input data as a function of the reservoir storage and treated as the average for the month.

Desalting plant

The capacity of the desalting plant is a fixed value for any given computation. However, by performing a series of computations, each with a different plant capacity in the range of feasible sizes, a best size plant can be determined.

The simulation does not depend directly on the kind of desalting process. The program does require that a plant capacity in MGD be specified and that the desalting plant cost data be supplied. The cost data consist of (a) fixed annual costs, (b) operational and maintenance costs, and (c) estimated turn-on and turn-off costs including mothballing. In the development and application of the Operating Rule Program, costs of brine disposal and distribution works are neglected, since they were not available. If this assumption is untenable in an application, then these costs must be determined and included in the cost data. For the subsequent application studies, cost data were furnished by the Oak Ridge National Laboratory, Oak Ridge, Tennessee, under contract with the Office of Saline Water.

In the event that the desalting plant is called upon to operate continuously for more than eleven months, a conditional turn-off is effected. If the twelfth month is not designated as a dry month, the plant is turned off for maintenance. Otherwise, the plant is continued in operation until a non-dry month is encountered. Other details of the simulated plant operation will be described in the section on the logic of the computer program.

Firm Yield

While firm yield is not a component of the model in the same sense as the parts discussed above, it is defined here because of its significance in developing the Operating Rule Program and in the system simulation.

Definition of firm yield

The firm water yield of a system must satisfy certain requirements and constraints as to water availability. The constraints may derive from economic, social, political, or other considerations. Such factors as frequency, magnitude, and duration of shortages each could serve to constrain or define the yield. A frequency constraint is used in the model presented herein. For example, a firm yield associated with a 95 percent probability implies that the system has water available to completely satisfy demands 95 years out of 100; i.e., 5 percent rate of failure. The level of frequency constraint on the firm yield is selected by the program user according to his willingness or aversion to accept the consequences of shortages.

The general model would probably be improved if the magnitude of shortages were included as a constraint on the firm yield. This feature should be investigated in later studies. The Operating Rule Program includes an option for listing the amounts of all annual shortages so that the user can judge the severity of the shortages and base his decisions on this information if desired when using the present program.

Cost of firm yield

If a desalting plant is to be used as a peaking plant to increase the firm or reliable yield which may be drawn conjunctively from a natural reservoir system, then the relevant product is not the volume of water produced in a given time by the desalting plant; rather it is the increase in capability to maintain sustained flow. This will be greater than or less than the capacity of the desalting plant depending on the definition of firm yield as will be apparent later. The relevant cost is not the cost of a unit volume of water produced by the desalting plant (normally expressed in cents per thousand gallons), but the cost over a given period of time to assure a unit increase in flow. Normally, costs are expressed in terms of annual cost in dollars of capital and operating expenses. With flow in MGD units the unit costs of safe yield would be expressed in dollars per annum per million gallons per day ($/year/MGD). A cost of $200,000/year/MGD means that $200,000 per year will pay for all of the fixed costs of capital and operating expenses to assure an increased firm yield of 1 million gallons per day.[1]

Logic of Program

In this section the overall methodology embodied in the Operating Rule Program will be discussed along with the role played by each of the component parts of the program. A macro flow chart of the logic employed in the Operating Rule Program is presented in Fig. 2, and will serve as the basis of discussion. Each block has been assigned a number which will reference that block as the logic of the computer program is explained. The program is written in Fortran IV computer language and consists of about 1700 statements.

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[1] This unit may be reduced to $/1000 gallons of additional firm yield by dividing by the number of days in a year and by 1,000. (In the example, $200,000/year/MGD becomes $0.5479/K gal.) The time units have now disappeared and only a cost per unit volume is given. But there is an important difference between a simple volume cost of desalted water in $/K gal. and a cost of firm yield in the same units. Purchased also is the assurance that the flow will be there *on demand;* i.e., present when needed without any constraints. *Firm yield* implies a time flow; the unit is really $/unit time/1000 gallons/unit time.

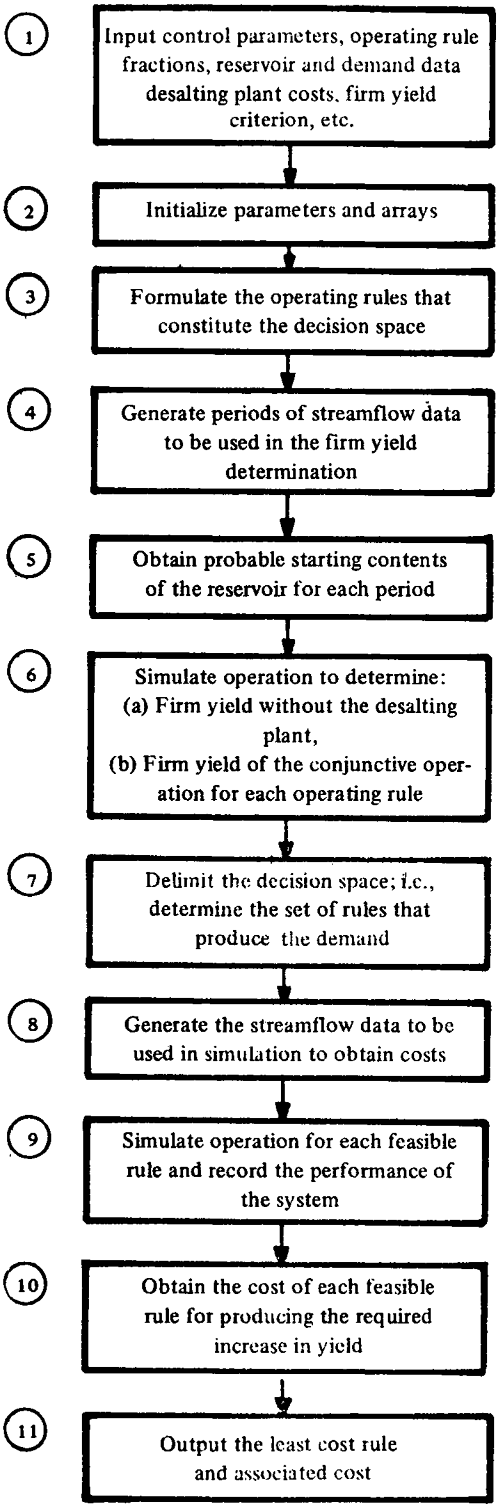

Figure 2. Operating Rule Program macro logic.

Block 1–Input

The simulation requires the following input to the program (A detailed description of the input format is presented in Appendix A under Input Data.):

1. *Control parameters.* Parameters that specify the length in years of the simulation period, number of periods of simulation performed, desalting plant size, options desired, and related items.

2. *Demand data.* The projected target demand rate and the monthly demand coefficients.

3. *Storage data.* Elevation-capacity-surface area curves in tabular form.

4. *Operating rule fractions.* Fractions of reservoir storage contents at any time that are to be used to decide when to turn the plant on and off. The procedure for combining these fractions to generate the set of operating rules is explained in block 3.

5. *Mandatory releases.* Releases for purposes other than municipal and industrial or other primary use. An average rate and the monthly coefficients must be given.

6. *Monthly season assignment.* Each month is described, on the basis of the historic record, as a low streamflow, average or a high streamflow month relative to other months of the year.

7. *Turn-on and turn-off increments.* These increments are used to refine the operating rule to account for the effect of the seasonal trends in streamflow. The turn-on and turn-off levels are adjusted according to the pre-assigned increments to modify the rule for wet and dry seasonal effects. A more detailed explanation of how these increments are used can be found in the discussion of block 3.

8. *Desalting plant cost data.* Included in these data are costs of operation at different load factors for plants optimized at specified load factors, interest rate, fixed charge rate, and estimate; turn-on and turn-off costs.

9. *Historical streamflow record.* This is the basic hydrologic record from which the operational hydrology subprogram derives the statistics for generating the streamflow sequences. This historical record is the best information that can be furnished as to the natural or unregulated monthly flows into the storage of the system.

Block 2–Initialization

Prior to simulating system operation, some initialization procedures are required. Certain arrays and parameters involved in summations are set to zero, daily flow rates are converted to monthly flow volumes, and the values of the variables involved in the simulation are altered to make the units consistent. All flow rates are converted to million gallons per day (MGD) and all volumes are converted to billions of gallons (BG).

Block 3–Formulation of operating rules

The objective of the computation is to find the optimum operating rule; i.e., the rule that will furnish the required additional firm yield at the least cost. The operating rule is the criterion for turning the desalting plant on or off. Both reservoir contents and the season of year are embodied in the rule. Each operating rule specifies a certain reservoir content below which the desalting plant will be operated and another reservoir content above which the desalting plant is turned off, but on standby.

For any given computation, the turn-on and turn-off fractions may be adjusted upwards or downwards by the program depending on whether the month under examination at the time is usually relatively wet or dry. During the simulation the state of the system is examined at the end of each month. If the storage content is below that specified by the operating rule and if the desalting plant is not operating, it is turned on for the ensuing month. If the storage contents are above that specified by the rule and the plant is operating, then it is turned off for the coming month

A set of operating rules can include three possible conditions: (1) The turn-on contents are less than the turn-off contents; (2) The turn-on and turn-off contents are equal; and (3) The turn-on contents are greater than the turn-off contents.

The first two conditions as shown in Figs. 3(a) and 3(b) present no special problems. When the contents of the system storage become less than that specified by the operating rule, the desalting plant is turned on. The plant is then operated until the contents of storage become greater than that specified by the rule.

The third condition as shown in Fig. 3(c) requires special treatment. The plant will be turned off when the storage contents become greater than the turn-off contents (point A) specified by the rule. The storage may subsequently be drawn lower before reaching the turn-on contents, in which case the desalting plant is turned on (point B), and operated until the time that the storage starts to increase again (point C).

A set of operating rules is formulated by the computer on the basis of the operating rule fractions (input item No. 4 specified by the user) and the seasonal turn-on and turn-off increments (input item No. 7 also specified by the user). Each one of the turn-on fractions selected for examination is combined with each of the turn-off fractions to form the set of operating rules.

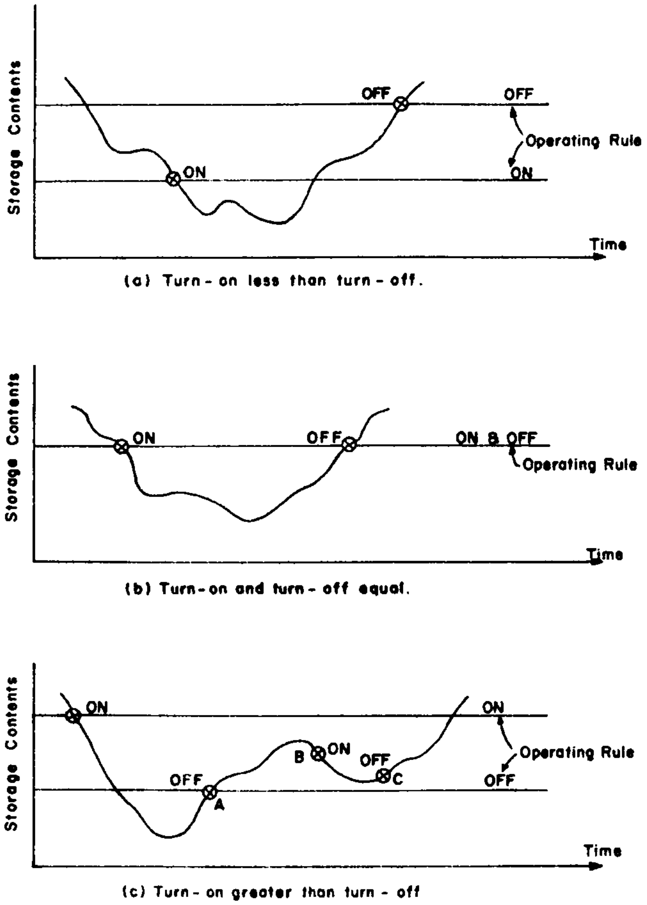

Figure 3. Possible conditions of operating rules.

Therefore, the number of rules for a particular run is given by

$$N_r = (N_{on}) (N_{off}) \qquad (4)$$

in which

N_r is the total number of rules in the set,

N_{on} is the number of turn-on fractions specified, and

N_{off} is the number of turn-off fractions specified.

The following example will serve to demonstrate how the rules are formed when subject to the following input:

Turn-on fractions = .80, .60, and .40
Turn-off fractions = .70, .60, and .50

Turn-on increments = .05 and .10
Turn-off increments = .05 and .10

One of the three possible cases can be specified by assigning 1, 2 or 3 to the input parameter NSN:[1]

1. A one-season characterization which implies little variation of mean monthly streamflow through a typical year.

2. A two-season characterization in which the monthly flows fit a pattern wherein some months are appreciably higher in flow than others, and

3. A three-season characterization in which each monthly flow is identifiable as either high, average, or low flow.

Table 2 summarizes a typical set of operating rules. If the one-season characterization is specified (NSN = 1), the operating rule is defined by column A in Table 1. Rule No. 5, for example, is turn-on = .60, turn-off = .70. No turn-on and turn-off increments are required and columns B and C are not needed for the simple one-season rule. If a two-season characterization is specified (NSN = 2), the operating rule is defined by columns A and B. Rule No. 3, for example, is turn-on = .80, turn-off = .60 for the months designated as low flow and turn-on = .75, turn-off = .55 for the months designated as high flow. One turn-on increment (.05) and one turn-off increment (.05) are required. Column C is not part of the rule. If the three-season characterization is specified (NSN = 3), all three columns define the rule. Rule No. 2, for example, is turn-on = .80, turn-off = .70 for months designated as low flow, turn-on = .75, turn-off = .65 for those months designated average, and turn-on = .70, turn-off = .60 for those months designated as the high flow months. As shown in the example, two turn-on and two turn-off increments are required. Judgment based on knowledge of the hydrologic conditions along with past experience with the program is used in specifying the seasonal characterization and the turn-on and turn-off increments.

Table 2. Typical set of operating rules.

Rule No.	Turn-on A	Turn-on B	Turn-on C	Turn-off A	Turn-off B	Turn-off C
1	Operation without the desalting plant					
2	.80	.75	.70	.70	.65	.60
3	.80	.75	.70	.60	.55	.50
4	.80	.75	.70	.50	.45	.40
5	.60	.55	.50	.70	.65	.60
6	.60	.55	.50	.60	.55	.50
7	.60	.55	.50	.50	.45	.40
8	.40	.35	.30	.70	.65	.60
9	.40	.35	.30	.60	.55	.50
10	.40	.35	.30	.50	.45	.40

Block 4–Generation of streamflow for firm yield

The streamflow generator, subprogram GNFLO, generates the streamflow sequences that are utilized in the firm yield analysis. The parameter, NPFY, specifies the number of periods to be generated, and the parameter, NYFY, specifies the number of years in each period. NPFY can vary in the range from 1 to 20 and NYFY cannot exceed 100 years. Considerations for selecting a value for NPFY and NYFY will be discussed under block 6.

Block 5–Selection of reservoir starting content

The reservoir storage contents at the beginning of a simulation period exert some influence upon the results obtained, particularly if the period of simulation is short. An arbitrary assumption as to initial contents of storage is considered inadequate. The problem is resolved by selecting, at random, a starting content from a sample of the distribution of year-end (or start of year) storage contents, for each period to be used in the simulation. The distribution, which is a function of the storage capacity, inflow and outflow is unknown. However, a 50-year sample of the distribution is obtained by simulating operation for 75 years and retaining the last 50 years of end of year contents. To start the simulation procedure for the 75 years, the initial contents are assumed to be one-half the storage capacity. The first 25 years of the simulation are rejected to eliminate the effect of the arbitrary starting point and are not considered as part of the sample.

Block 6–Firm yield analysis

In the first phase of the simulation the program obtains the firm yield of the system for the following two different conditions:

[1] Seasonal configuration of the mean monthly inflows (see Appendix A).

1. The existing supply system without any desalted water supplement.

2. The system when operated in conjunction with a desalting plant. This entails finding the firm yield for every operating rule formulated in block 3.

The procedure for obtaining the firm yield depends upon the definition of firm yield furnished by the program user. If a drought proof condition, i.e., 100 percent frequency of meeting demand, is specified, a straight iterative procedure is used in which successive guesses are made and checked until the yield is found that can be met all the time. If a firm yield definition of less than 100 percent is furnished, then a *quasi* iterative procedure is used. This procedure involves finding a firm yield above and below that which can be met the specified percent of time and then an interpolation is performed to obtain the desired firm yield.

Four input parameters are involved directly in the iterative procedure:

1. An estimate of the yield of the natural system expressed as a decimal fraction of the mean inflow rate (SSTART),

2. An increment used to modify (SSTART) while iterating to find the firm yield (STEP),

3. The firm yield definition expressed as a frequency of meeting the target demand (PCF), and

4. The mean inflow rate to the system (DEMB).

If the system had unlimited storage and no losses, the demand that could be furnished 100 percent of the time would be the mean flow rate into the system. However, as this condition does not exist, the problem becomes that of finding the yield that will satisfy the firm yield definition.

An average demand rate is obtained as follows:

$$\overline{R} = f \cdot \overline{Q} \quad \ldots\ldots\ldots\ldots (5)$$

in which

- $\overline{R}$ is the average demand rate,
- $\overline{Q}$ is the mean inflow rate (DEMB), and
- f is the fractional level of yield (SSTART), $0.0 < f < 1.0$.

For example, if $\overline{Q}$ = 350 MGD and f = 0.80, then the average demand rate imposed on the system is $\overline{R}$ = 280 MGD. Simulation then proceeds by routing a period of generated streamflow through the system subject to the monthly demand rates obtained from Eq. (2).

The basic storage equation involved in the simulation is

$$I - O = \Delta S \quad \ldots\ldots\ldots (6)$$

in which

- I is the inflow,
- O is the outflow, and
- ΔS is the change in storage.

Substituting for each term of Eq. (6) its components treated as rates, gives the following equation:

$$(\Delta S)_{i,j} = q_{i,j} + w - e_i - (r_i)_t - (r_i)_m$$

$$\text{for } i = 1, 2, \ldots, 12; \quad j = 1, 2, \ldots, \text{NYP} \quad \ldots\ldots (7)$$

in which

- $q_{i,j}$ is the streamflow rate for month, i, year, j,
- w is the desalting plant rate,
- e_i is the evaporation rate for month, i,
- $(r_i)_t$ is the target demand rate for month, i,
- $(r_i)_m$ is the mandatory release rate for month, i, and
- $(\Delta S)_{i,j}$ is the change in storage for month, i, year, j.

The state of the system is examined prior to the start of each month by converting each term on the right-hand side of Eq. (7) to a volume (BG) on the basis of the number of days in the given month and solving

$$S_{i+1,j} = S_i + Q_{i,j} + W_i - E_i - (R_i)_t - (R_i)_m \quad \ldots\ldots\ldots (8)$$

in which

- $S_{i+1,j}$ is the storage contents at the start of month i + 1 (or end of month, i), year, j,
- S_i is the storage contents at the start of month, i, year, j, and
- all other terms correspond to their counterparts in Eq. (7).

The value of $S_{i+1,j}$ is compared to the operating rule and the appropriate action is initiated to turn the plant on or off or leave it unchanged. During simulation without the desalting plant, W_i in Eq. (8) is zero for every month.

During the simulation the response or behavior of the system is recorded by the program. The amount of shortage, average duration of shortage, and frequency of satisfying the demand are computed for the length of period specified by the parameter NYFY. The average plant load factor (based only on the years the plant operates and not on total years simulated) is also determined by the following equation:

$$L_r = \frac{1}{N_{op}} \sum_{j=1}^{N} \left(\frac{O_j}{12} \right) \quad \ldots\ldots (9)$$

in which

L_r is the average plant load factor for rule r, r = 1, 2, ..., N_r,

O_j is the number of months the plant operated in year, j, $0 \leq O_j \leq 12$, as counted by the program,

N is the number of years in the period (NYFY), and

N_{op} is the number of years that the plant operated in the simulation as counted by the program and

N_r is the number of operating rules in the set.

Thus, the plant load factor defined above reflects the fraction of time that the plant runs in those years that the plant is turned on. Years in which the plant does not operate are not included. The plant load factor influences the design of the desalting plant since it reflects the yearly wear and tear on the operating plant. A gross load factor should also be defined which would include all years (N) in the denominator of Eq. (9) rather than just those years when the plant runs (N_{op}).

The frequency of satisfying the demand is determined as follows:

$$F_t = (1.0 - \frac{1}{N} \sum_{j=1}^{N} K_j) \; (100) \quad . . (10)$$

in which

F_t = frequency of satisfying the demand (on a yearly basis),

K_j = 1 if one or more shortages occurred in year, j, and

K_j = 0 if no shortage occurred.

The nature of the firm yield criteria necessitates two different iterative procedures for (a) firm yield specifications less than 100 percent and (b) firm yield specifications equal to 100 percent.

Firm yield specifications less than 100 percent. The value of F_t calculated by Eq. (10) is compared with the specified reliability of firm yield, F_y, in Eq. (11).

$$(F_y - \Delta) \leq F_t \leq (F_y + \Delta) \quad . . . . (11)$$

The value of Δ was chosen as 1.0 percent. If Eq. (11) is satisfied, then the average demand rate as computed from Eq. (5) is the firm yield for the given period. If Eq. (11) is not satisfied, f is adjusted in Eq. (5) and the simulation repeated with the different demand rate. The process is repeated until two nearby values of F_t are obtained (designated by ' and '') such that $F_t' < (F_y - 1.0)$ and $(F_y + 1.0) < F_t'' < 100$. Once this condition is achieved, a linear interpolation is performed to obtain the value of firm yield for the given period. The method is demonstrated graphically in Fig. 4.

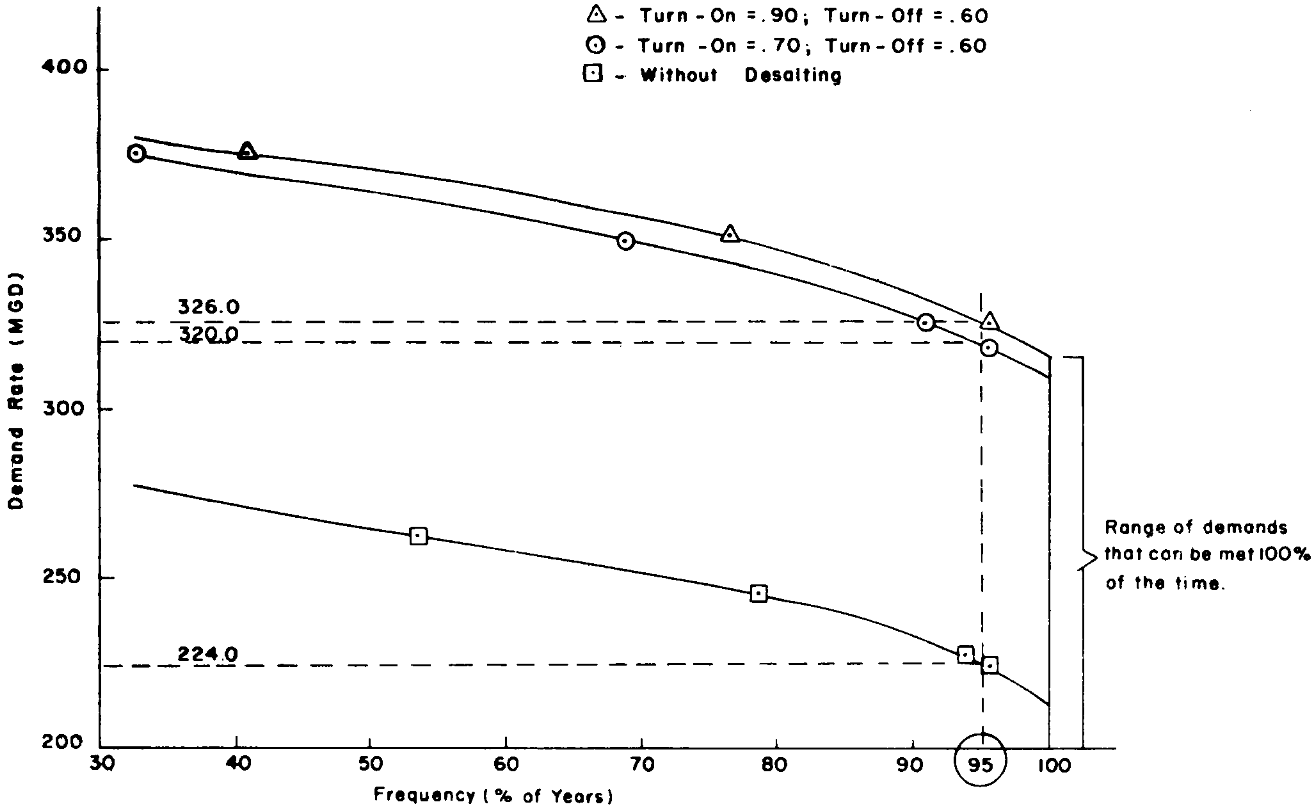

Figure 4. Procedure for determining firm yield.

Firm yield specification equal to 100 percent. There are many demand rates that can be satisfied 100 percent of the time as can be seen in Fig. 4. The procedure used in this case is to alter the demand rate by adjusting f in Eq. (5) until the largest demand rate is reached that will still satisfy

$$99.0 \leq F_t \leq 100.0 \quad \ldots\ldots (12)$$

The iteration is terminated when the change (Δ f) in f to get from $F_t > 100.0$ in the k^{th} iteration to $F_t < 100.0$ in the $k^{th} + 1$ iteration is less than 1.0 percent. Because of the nature of this iteration, much more computational effort is required to locate the desired firm yield value than in the preceding case.

A firm yield for operation without desalting and for each operating rule in the set of rules is determined as outlined above. If the number of periods specified (NPFY) is greater than one, the whole procedure is repeated, until simulation has been performed for NPFY periods. The results from the different periods are averaged and a set of firm yield values for each operating rule is obtained as follows:

$$\bar{Y}_n = \frac{1}{N_p} \sum_{i=0}^{N_p} (Y_n)_i$$
$$\text{for } n = 0, 1, 2, \ldots, N_r \quad \ldots (13)$$

in which

- Y_n is the average firm yield for rule, n,
- $(Y_n)_i$ is the firm yield for rule n and period, i,
- N_p is the number of periods,
- N_r is the number of operating rules, and
- Y_o is the firm yield of the system without desalted supplement.

Average operating load factors are obtained for each operating rule as

$$\bar{L}_r = \frac{1}{N_p} \sum_{i=1}^{N_p} (L_r)_i$$
$$\text{for } r = 1, 2, \ldots, N_r \quad \ldots (14)$$

in which

- $\bar{L}$ is the average load factor for rule, r,
- $(L_r)_i$ is the load factor for rule r period, i.

The number of periods and the number of years per period selected for the simulation are specified by the user. Confidence in the results varies directly with the number of periods used; however, there is a practical upper limit set by the amount of computational effort involved compared to the amount of new information generated. The version of the computer program documented herein allows a maximum of 20 periods and a maximum of 100 years per period. The length of period chosen is influenced by the useful life of the system and should be at least as long as the years of simulation in the cost analysis of block 10. In the subsequent application studies, five periods of 75 years per period are used.

Block 7—Determination of feasible operating rules

The decision space is defined as the set of operating rules that are formulated in block 3. The set may not contain the overall optimum rule unless care is exercised in specifying the turn-on and turn-off fractions. By an examination of the computer output, it can be determined whether the overall optimum rule was located or not. One limitation on the feasible rules is the specified target demand rate. Obviously, the rules having firm yields less than the target demand need not be considered. Those rules producing more yield than required can be removed from consideration because of their lower efficiency. Thus many of the operating rules of the decision space are removed from further consideration and only those rules furnishing yields very close to the target demand are retained for further examination.

A set of feasible operating rules is obtained by performing an interpolation of the firm yield array. The array involves three variables because each entry has a value for the firm yield, a turn-on level, and a turn-off level. The interpolation is performed by entering with the target demand rate as the argument and interpolating to obtain a turn-on fraction for each turn-off specified in the input. The interpolation procedure is illustrated graphically in Fig. 5. Three turn-off fractions are used with a target demand rate of 280 MGD. A linear interpolation is used to obtain the feasible set of rules shown in Table 3.

Table 3. Feasible operating rules.

Turn-on	Turn-off	Load factor
.59	.80	.61
.62	.60	.62
.68	.40	.64

An average plant load factor for each feasible rule is determined by averaging the load factors associated with the two rules involved in the interpolation. Thus, if the r^{th} and the $r^{th} + 1$ rule enter into the linear interpolation,

$$\bar{L}_f = \frac{\bar{L}_r + \bar{L}_{r+1}}{2} \quad \ldots\ldots (15)$$

in which

- $\bar{L}_f$ is the load factor for the feasible rule,
- $\bar{L}_r$ is the load factor associated with the r^{th} rule,
- $\bar{L}_{r+1}$ is the load factor associated with the $r^{th} + 1$ rule.

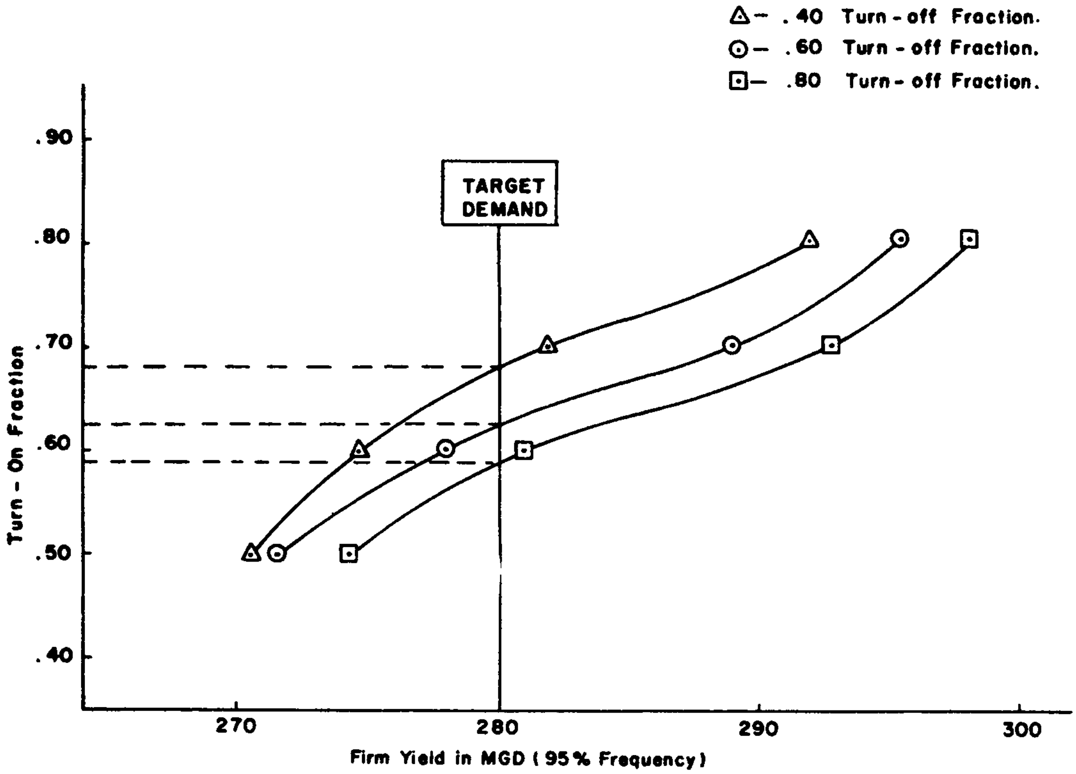

Figure 5. Feasible rule determination.

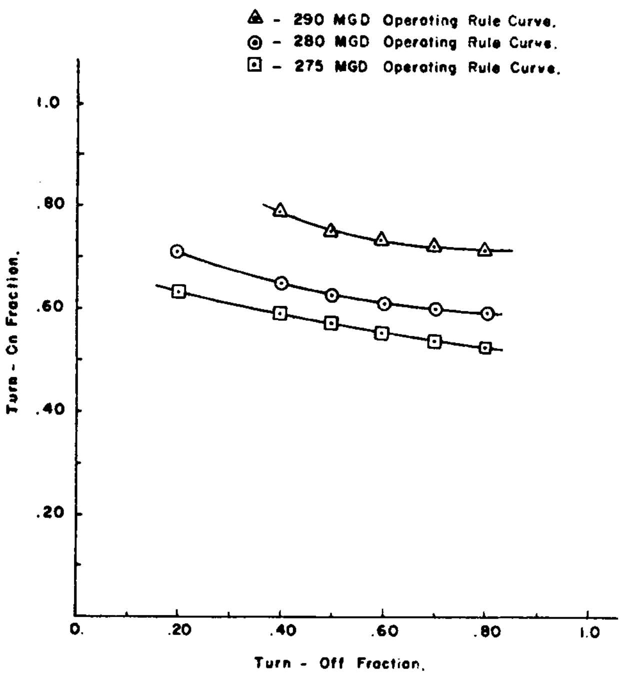

Figure 6. Feasible operating rule curves.

A linear interpolation was selected because it was not subject to erratic results as frequently as interpolations based on higher degree polynomials.

Fig. 6 shows a set of feasible operating rule curves for three different target demand rates. Since all points plotted are feasible rules, the curves can help suggest other feasible rules that might be investigated in further stages of the analysis to more closely define the optimum rule.

Block 8–Generation of streamflow for simulation

Subprogram GNFLO is called to generate streamflow for the second phase of simulation. The number of periods is specified by the parameter NPER and the number of years per period by NYP. The number of years per period is taken as some multiple of the useful life of the desalting plant. In the applications that follow 5 periods of 30 years each were used.

Block 9–Simulation with feasible rules

Simulation of the system is performed for each rule in the set of feasible operating rules. The purpose of this phase of simulation is to record those parameters of system performance required in the economic or cost analysis.

A sequence of streamflow is routed through the system and for each year the following parameters are recorded and printed out as in Figs. 16, 17, 18 and 19 (the names printed in capitals identify column names in the figures):

(a) The number of times the desalting plant is turned on, TIMES ON.

(b) The number of times the desalting plant is turned off, TIMES OFF.

(c) The number of months the desalting plant operates, MONTHS ON.

(d) The amount of desalted water produced, DSPRO.

(e) The total amount of desalted water that is spilled, DSSP, regardless of whether it was produced in the year in question or in earlier years. The first water over the spillway is assumed to be desalted water if extra water has been produced since the last spill.

(f) The total amount of water that is spilled, including both desalted water and natural water, SPILL.

(g) The total amount of shortages, SHORT.

Simulation is performed NPER periods for each rule.

Block 10–Cost analysis

Based on the performance of the system, as recorded in block 9, the cost of producing the additional firm yield is determined for each feasible operating rule.

$$\Delta\overline{Y} = D_t - \overline{Y}_o \quad . . . . (16)$$

where, in units of MGD,

$\Delta\overline{Y}$ is the additional firm yield
D_t is the projected target demand rate, and
$\overline{Y}_o$ is the firm yield rate without desalting (determined in block 6).

The performance parameters from block 9 as well as a cost table like that shown in Fig. 8 are required in the cost analysis. The items of the cost tables are:

(a) Discount interest rates (fraction),
(b) Estimated turn-on and turn-off costs (dollars),
(c) Annual fixed charges (dollars/year), and
(d) Operation and maintenance costs (dollars/year).

Each column of the table represents the costs for a desalting plant, of specified capacity, that is optimized at the indicated design load factor. The rows are the yearly operating and maintenance costs for the indicated operational load factors. In analyzing the cost of an operating rule, the column of cost data is used whose load factor most nearly corresponds to the load factor associated with the rule, L_f. For example, all three rules shown in Table 2 would be analyzed using the data in column five (load factor = .70) in Fig. 8.

In order to assign a cost to ΔY it is necessary to obtain an equivalent uniform annual cost for the plant performance of the simulated operation. The fixed charges, U_f, enter the computation as uniform annual payments and include:

(a) Interest on initial capital,
(b) Amortization of initial capital,
(c) Interim replacements, and
(d) Taxes and insurance.

Operation and maintenance costs vary from year to year and, therefore, must be converted to a uniform annual series. The present value of all operation and maintenance costs is determined and then converted to a uniform annual payment by using a capital recovery factor. The present value is obtained as follows:

$$V_p = \sum_{j=1}^{N} \frac{1}{(1+I)_j} \cdot [(C_1)_j + (C_2)_j] \quad . . (17)$$

in which

V_p is the present value of the operation and maintenance costs,
$(C_1)_j$ is the operation and maintenance cost in year, j,
$(C_2)_j$ is the turn-on and turn-off cost in year, j,
I is the discount interest rate, and
N is the number of years in the economic period.

C_1 is obtained by interpolating in the appropriate column of the cost data table. The number of months the plant operates each year is converted to a load factor and a linear interpolation is performed to obtain the associated cost. C_2 is a summation of the number of times the plant is turned on and turned off each year multiplied by the cost of each event.

The uniform equivalent annual cost for operation and maintenance, U_o, is determined by

$$U_o = V_p \cdot \frac{I(1+I)^N}{[(1+I)^N - 1.0]} \quad . . . . (18)$$

in which V_p, I, and N are the same as in Eq. (17).

A total uniform yearly cost for a period of simulation is given by

$$T_u = U_o + U_f \quad \text{. . . . .(19)}$$

in which T_u is the uniform annual cost in dollars and U_f is the annual fixed charge. The cost of additional firm yield, C_u, is then computed as:

$$C_u = \frac{T_u}{\Delta \overline{Y}}$$

in \$/yr. per MGD of additional firm yield . . . . (20a)

$$\text{or} \quad C_u = \frac{T_u \times 10^{-5}}{3.65\ (\Delta \overline{Y})}$$

in \$/1000 gal. of additional firm yield . . . . . (20b)

in which $(\Delta \overline{Y})$ is the increase in firm yield (MGD) and the constants convert the cost to the desired units.

Block 11–Determination of least cost rule

From the values of C_u obtained in block 10, an average cost of each rule is computed as

$$\overline{C}_i = \frac{1}{N} \sum_{j=1}^{N} (C_u)_{i,j}$$

$$\text{for } i = 1, 2, \ldots, N_f \quad \text{. . . . .(21)}$$

in which

$\overline{C}_i$ is the average unit cost of the i[th] feasible rule,

$Cu_{i,j}$ is the unit cost of the i[th] rule for period j,

N is the number of periods (NPER), and

N_f is the number of feasible rules.

The preferred rule from the feasible set of operating rules is readily identified as the one with the minimum cost; i.e., C_{min}.[1] The optimum operating rule and the associated cost are printed out and the computation is terminated.

Optimum plant size and reservoir size

Since the plant size and reservoir size are each fixed for a given computation, the program does not automatically determine the optimum plant size and optimum reservoir size. These can be determined manually by running the program for several combinations. The program could be modified to include a gradient procedure on the cost function with the plant size and reservoir size as decision variables. Such a change in the program was considered but deferred because of the large increase in the computer time that would be required for most applications. Further work on this program modification is suggested as part of future investigations. A skilled operator can probably save money (compared with automatic operation) by judicious selection of successive runs for determining optimum plant size. The reservoir size is usually constrained by the existing physical conditions to a single value.

[1] Some other criteria might have been used; such as, the rule which would provide the greatest new safe yield at marginal value of water or marginal cost of water from an alternative source.

APPLICATION OF THE OPERATING RULE PROGRAM TO SELECTED SYSTEMS

As specified in the contract, the Operating Rule Program has been applied to three "natural water-reservoir systems" to determine the minimum cost of additional firm yield for selected desalting plants of various sizes and the operating rule associated with minimum cost. The program also furnishes the information needed to choose the optimum size of plant for each system.

The three systems selected (in consultation with the Office of Saline Water) were the Cachuma project in California, the New York City Water System, and the Deer Creek Reservoir of the Salt Lake City water system.

These applications are designed to demonstrate the methodology and effectiveness of the Operating Rule Program by using real environments. In applying the Operating Rule Program to the three selected cases for study purposes, the single purpose, multi-stage flash distillation (MSF) process plant was used. Basic engineering and cost data for plants used in the study are given in detail in Appendix C. These data were developed by the Oak Ridge National Laboratory under its contract with OSW. Plant capacities ranging from 25 to 100 MGD, plant load factors from 10 percent to 90 percent, a fuel cost of 35¢/MBTU, interest rate of 4-5/8 percent and a 30-year plant life were considered. For plant sizes larger than 100 MGD, ORNL furnished the set of arithmetic multipliers given in Appendix C. The 100 MGD plant was considered as the base and the multipliers were used to compute the cost tables for the larger plant sizes up to 300 MGD.

Water costs derived herein are for the incremental supply of safe yield produced by the desalting plants during their period of conjunctive operation. The costs shown are discounted over the 30-year selected study period (plant lifetime) and levelized to show a uniform annual safe yield cost for the period. Only the costs that occur within the plant boundary were considered.

While the MSF process was utilized in the study, other processes such as the membrane processes could have been considered equally as well. As in the MSF process case, relevant input data would have to be derived and fed into the program.

The cost, inputs and results shown in these applications are only illustrative of the application of the Operating Rule Program and proof of its operability. Much more detailed study would be required to determine the cost input factors to be used in actual feasibility studies involving conjunctive operation. Results obtained for the cases selected, therefore, are not necessarily comparable to those which might be obtained from a more detailed feasibility study for the same site. Contract time and funds did not permit detailed investigation of input parameters. The main effort in the application has been to demonstrate the method and the computer program in a realistic way. Less emphasis and effort has gone into determining and verifying the input data.

Cachuma Project Application

Purpose

The purpose of this application study is to find the lowest cost conjunctive operation desalting alternative to increase the firm yield of the Cachuma Project to 80 MGD with reservoir size held constant. The cost of supplying the increased firm yield, the optimum size plant, and the associated optimum operating rule are to be determined.

System description

The Cachuma dam and reservoir are located northeast of Santa Barbara, California. The 66.8 billion gallon reservoir has a dead storage of 10.6 BG, thus leaving a usable storage content of 56.2 BG. The Santa Ynez River is the only major inflow to the reservoir. This highly variable stream has a mean yearly inflow of 77.3 MGD based on 59 years of record. Other features of the project include the Tecolote tunnel, the South Coast conduit with its four regulating reservoirs and distribution systems to serve the south coast area including the city of Santa Barbara.

Because of the highly irregular flows of the Santa Ynez River, this site was selected for investigation of the use of desalting as a supplemental source to augment the natural flow of the river as regulated by the reservoir. In such a system the desalting plant would be located on the coast and its production would be fed into the system near Santa Barbara—probably into one or more of the regulating reservoirs. During times when desalted water is needed it would be blended with natural waters. The flow through Tecolote tunnel would be reduced by the amount of desalted water production and the desalted water would thus be "stored" by exchange in the Cachuma Reservoir.

Input data

The flow of the Santa Ynez River tributary to the Cachuma Dam constitutes the hydrologic input data for this application and is given in Table 4. The data were taken from a report of the Bureau of Reclamation (1968).

Table 4. Inflow to Cachuma in ac-ft.

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT
1905	800	200	200	3000	79400	89800	13800	5300	1500	200	100	100
1906	100	0	0	600	1000	117900	15200	6900	2300	600	100	100
1907	100	0	2100	174600	46900	235100	22700	7000	3400	700	200	100
1908	1500	0	100	17800	59500	21700	7200	4500	2300	1100	100	100
1909	0	0	200	60000	180200	100300	53100	19600	6700	2700	600	0
1910	0	0	2100	28900	4400	9100	5400	2000	600	100	100	100
1911	100	0	0	33300	33400	211100	22200	9400	4300	1700	600	200
1912	600	300	500	600	400	9100	6300	2800	800	200	0	0
1913	0	0	0	300	8900	7300	2200	1300	600	100	100	0
1914	0	800	300	143900	173200	30000	9400	5100	2300	900	200	100
1915	100	0	800	2700	47600	17300	7700	14100	2600	900	200	100
1916	400	200	800	92000	27200	15800	5700	3000	1100	600	400	100
1917	600	200	7600	10700	25800	13100	4100	2400	800	100	0	0
1918	100	0	100	0	31200	108100	16500	5500	2000	400	200	400
1919	0	3700	1800	11500	3800	5300	0	2500	0	0	0	1700
1920	200	0	300	200	1600	9800	4500	1500	600	200	100	100
1921	0	0	0	800	1000	1400	400	900	200	100	100	0
1922	0	0	12400	12000	46700	20700	8400	4300	1500	400	0	0
1923	0	0	2300	700	1500	1200	900	900	200	100	100	0
1924	0	0	0	0	0	800	200	100	100	0	0	0
1925	0	0	0	0	0	400	1000	400	100	0	0	0
1926	0	0	100	0	5700	700	58000	1900	600	100	0	0
1927	0	3100	1800	1300	52500	14900	5500	800	400	100	100	100
1928	0	0	200	100	3300	2600	600	400	100	0	0	0
1929	0	0	100	0	500	1000	600	100	0	0	0	0
1930	0	0	0	0	0	2300	200	300	100	0	0	0
1931	0	0	0	0	0	0	0	100	100	0	0	0
1932	0	0	4700	1800	48900	4600	2100	1100	200	0	0	0
1933	0	0	0	4600	2400	1400	500	400	100	0	0	0
1934	0	0	0	5200	6200	2600	900	200	100	0	0	0
1935	500	0	0	9600	3300	8000	15300	3400	700	0	100	0
1936	0	0	0	0	18300	4500	4000	800	200	0	0	0
1937	0	0	3000	3400	58300	57300	19200	5800	2200	200	200	100
1938	0	0	300	200	53800	177700	18200	7000	3400	1500	300	100
1939	0	0	600	1200	3100	6900	2100	1200	200	0	0	500
1940	0	0	0	800	2300	3100	1500	300	200	0	0	0
1941	0	0	3000	24800	93600	162800	116100	[illegible]	7900	[illegible]	1800	1000
1942	700	500	3100	3900	2900	3700	7600	3700	1200	100	100	0
1943	0	0	0	63700	28000	64000	13400	4800	2100	500	100	100
1944	100	0	300	800	36300	35800	7100	4000	1500	400	100	100
1945	0	1100	400	500	16000	10300	5000	2000	600	200	0	0
1946	0	0	4400	1400	2000	13600	9600	1800	500	100	100	0
1947	0	1500	2900	2400	1200	900	200	300	0	0	0	0
1948	0	0	0	0	0	0	0	100	0	0	0	0
1949	0	0	0	0	0	200	200	200	0	0	0	0
1950	0	0	0	0	1000	100	300	200	0	0	0	0
1951	0	0	0	0	0	0	0	0	0	0	0	0
1952	0	0	1100	81400	8700	64900	16700	6100	2400	1000	600	0
1953	100	500	2400	5100	1700	1100	900	1000	200	0	0	0
1954	0	0	0	3000	1700	7400	5100	1200	300	0	0	0
1955	0	0	0	600	800	1000	500	2100	300	200	100	100
1956	100	0	3700	11900	2300	1600	2500	3600	500	200	100	100
1957	0	0	0	600	1500	1500	1000	1300	200	100	100	100
1958	0	0	1400	1500	39600	56000	128900	12100	4300	1200	200	200
1959	0	100	100	900	11000	2400	1100	500	200	300	100	200
1960	100	0	0	0	1700	500	300	300	100	100	100	0
1961	0	0	100	0	300	0	0	0	0	0	0	0
1962	0	0	0	100	100200	18100	5300	2600	600	100	100	0

The reservoir capacity data appear in Table 5. Monthly evaporation potential for Cachuma Reservoir is given in Table 6. Other typical input data are shown in the page of printout in Fig. 7, including the demand rate, monthly season assignments and increments, demand coefficients, release coefficients, and the length and number of periods of flows used in the computations.

Table 5. Elevation-capacity data.

CACHUMA RESERVOIR

Water surface elev. in feet	Capacity in Res. in ac-ft
560.	0.
565.	1.
570.	12.
575.	78.
580.	276.
585.	708.
590.	1419.
595.	2263.
600.	3114.
605.	4156.
610.	5364.
615.	6719.
620.	8229.
625.	9965.
630.	11945.
635.	14251.
640.	17023.
645.	20275.
650.	23985.
655.	28095.
660.	32514.
665.	37305.
670.	42628.
675.	48513.
680.	54874.
685.	61738.
690.	69129.
695.	77040.
700.	85530.
705.	94580.
710.	104163.
715.	114385.
720.	125292.
725.	136861.
730.	149099.
735.	162004.
740.	175569.
750.	204874.
755.	220694.
760.	237200.

Table 6. Monthly evaporation potential, Cachuma Reservoir.

Month	Evaporation (Inches)
Oct.	5.39
Nov.	3.79
Dec.	2.92
Jan.	2.69
Feb.	2.91
Mar.	4.38
April	5.67
May	6.97
June	8.54
July	9.66
Aug.	8.70
Sept.	7.04

The first information needed from the Operating Rule Program is the amount of firm yield that the system can supply without the help of the desalting plant. This yield is given in Table 7 along with other results from the Cachuma application. Knowing both the demand that must be met and the firm yield without desalting, the firm yield to be added by the desalting plant can be determined by subtraction. The sizes of desalting plants to be studied can then be chosen.

Of the many sizes of plants that could have been selected, 60, 65, 75, and 85 MGD plants were analyzed. One would expect that several plant sizes could meet the demand for water. Too small a plant would, however, run almost continuously and would spill water frequently due to its high turn-off fraction and thus would be less efficient than a larger plant. On the other hand, too large a plant would sit idle much of the time with a consequent drop in efficiency.

In selecting the plant sizes to be studied, the judgment and experience of the operator are important. The first computation should be made with a plant that is expected to be in the middle of the range of plant sizes. Based on experience with cases studied using the program, the best size is usually a plant with a capacity about 1.30 times as large as the required increase in firm yield. From the information supplied by the first computation, the decision is made as to the next plant size (somewhat smaller or larger) whose operation is to be simulated. Thus the process continues with the operator deciding at each stage the next plant size to be analyzed, until the optimal plant size is determined as that plant which supplies the needed increase in firm yield at the lowest cost when operating with the optimum operating rule.

The firm yield analysis, made by the computer program showed that the 60 MGD plant could not meet

Figure 7. Input data, Cachuma application.

```
   CACHUMA APPLICATION WITH A 75 M.G.D. DESALTING PLANT

NO.OF PERIODS IN SIMULATION=  5          NO. OF YEARS IN FACH PERIOD=  30
NO.OF PERIODS IN FIRM YIELD=  5          NO.OF YEARS IN EACH PERIOD=  75

NPRC= 40
CMAX= 66.789 B.G.
CMIN= 10.600 B.G.
DSCAP= 75.00 M.G.D.
FORCE= 1
KIO= 1
KPC= 2
KIP= 2
KREAD= 1
IFLOW= 3
ISTOR= 1
IYEAR= 1
KIK= 1

THERE ARE  1 DEMAND LEVELS IN THIS RUN AS FOLLOWS
       80.0

DEMB=  77.300 M.G.D.
RBAR=    .000 M.G.D.


THIS IS A 3 SEASON RUN
AVE. SEASON ON INC= .025          AVE. SEASON OFF INC= .025
WET SEASON ON INC.= .050          WET SEASON OFF INC.= .050
```

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT
MONTHLY SEASON ASSIGNMENT	1	2	3	3	3	2	2	1	1	1	1	1
DEMAND COEFFICIENTS	1.23	.76	.40	.36	.28	.59	.76	1.07	1.32	1.86	1.89	1.50
RELEASE COEFFICIENTS	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00

```
TURN-ON FRACTIONS       .50  .40  .30
TURN-OFF FRACTIONS      .60  .50  .40  .30

START= .60
STEP= .05
PCF= .95
```

Table 7. Summary of cost computations, Cachuma application.

Line No.	Probability level defining firm yield %	Demand MGD	Firm yield without desalting MGD	Required increase in firm yield MGD	Plant size MGD	Optimum rule (reservoir fraction full) ON	OFF	Average plant load factor %	Desalted water use/production ratio (efficiency)	Number of feasible rules tried	Average levelized cost in $/yr per MGD of added firm yield
1	95	80.0	24.16	55.84	65	0.80	0.95	81	0.72	2	214,600
2	95	80.0	24.16	55.84	75	.36	.40	65	0.82	4	197,500
3	95	80.0	24.16	55.84	85	.22	.20	56	0.87	3	201,400
4	99	80.0	20.97	59.03	75	.44	.60	67	0.79	4	195,100
5	90	80.0	28.17	51.83	75	.30	.30	63	0.85	4	207,400
6	95	80.0	24.16	55.84	75	.39	.40	64	0.83	3	196,800
7	95	80.0	24.16	55.84	75	.37	.40	64	0.82	3	197,900
8	95	80.0	24.16	55.84	75	.47	.30	62	0.82	3	200,100
9	95	80.0	26.96	53.04	75	.31	.30	63	0.84	3	197,800
10	95	80.0	25.56	54.44	75	.26	.25	64	0.78	2	192,300
11	95	80.0	25.56	54.44	65	.61	.70	72	0.79	4	201,000
12	95	80.0	24.16	55.84	75	.36	.40	65	0.83	4	183,700
13	95	80.0	24.16	55.84	75	.36	.40	65	0.82	4	221,700
14	95	80.0	24.16	55.84	75	Base Load		90	-	-	259,300
15	95	80.0	24.16	55.84	65	Base Load		90	-	-	226,200

Standard conditions unless otherwise noted

- Useful plant life = 30 years
- 5 simulation periods of 30 years each
- 5 firm yield periods of 75 years each
- Seasonal increments of 0.025 and 0.050
- Reservoir capacity = 66.79 BG
- No special release requirements
- Demand coefficients (starting in October) are 1.23, 0.76, 0.40, 0.36, 0.28, 0.59, 0.76 1.07, 1.32, 1.86, 1.89, 1.50
- Fixed charge rate = 7.23%
- Interest rate = 5.0%

Line	Special conditions
6	Seasonal increments = 0.05 and 0.10
7	Two season assignment. Increment = 0.05. (NSN = 2)
8	One season assignment (NSN = 1)
9	Reservoir size = 76.79 BG
10,11	Uniform demand coefficients
12	Useful life = 50 years
13	Operating costs increased by 25%
14	Base Load Operation (90% of time)
15	Base Load Operation (90% of time)

the projected demand with any operating rule. Therefore, it was dropped from any further study.

The economic data for the cost computations are shown in the page of printout in Fig. 8 for the 75 MGD plant. Table 7 summarizes the cost computations for the Cachuma Project applications. This table also shows the sensitivity of the cost of the added firm yield to changes in the values of certain input parameters. The sensitivity analysis is discussed later.

Basic results

From the many possible operating rules for the 75 MGD plant, with firm yield defined at 95 percent probability, the program found four feasible rules for detailed simulation and cost comparison. These rules were ON at .32 and OFF at .60, ON at .32 and OFF at .50, ON at .36 and OFF at .40, and ON at .50 and OFF at .30. Uniform annual water costs determined for these rules are respectively $199,600, $199,300, $197,500 and $199,600/year/MGD of added firm yield. Thus the third rule has a slight advantage over the others for this plant, but each of these four rules perform almost as well as the others. Details of the optimum rule computation are shown in line 2 of Table 7.

To assist in visualizing how the system operates, Figs. 9 and 10 show a typical inflow hydrograph and the reservoir contents with and without the desalting plant operating. Shown on Fig. 10 are the plant turn-on and turn-off contents and the dead storage. Whenever the reservoir contents drop below the ON level, the desalting plant is operating and whenever contents are above the OFF level, the plant is shut down. The demand that can be satisfied in each case is given in Fig. 10. The conditions of the computation are the same as for line 2, Table 7.

Prior to the final simulation and cost computation, the program first eliminates from further consideration all rules that cannot produce enough water to satisfy the demand. Then the program eliminates those rules which

Figure 8. Cost data, Cachuma application.[a]

COST DATA FOR DESALTING PLANT USED IN ANALYSIS

OPER. L. F. (IN PERCENT)	ANNUAL COST IN $/YR. FOR THE PLANT THAT IS OPTIMIZED AT THE GIVEN LOAD FACTOR (IN PERCENT)				
	40.	50.	60.	70.	80.
0.	32000.	32000.	32000.	32000.	32000.
10.	1216000.	1168000.	1141000.	1113000.	1092000.
20.	2284000.	2184000.	2131000.	2078000.	2071000.
30.	3351000.	3199000.	3120000.	3040000.	2984000.
50.	5486000.	5230000.	5038000.	4965000.	4875000.
70.	7621000.	7261000.	7076000.	6891000.	6767000.
90.	9693000.	9229000.	8991000.	8753000.	8594000.
100.	10738000.	10229000.	9961000.	9693000.	9524000.
ANNUAL FIXED CHG. AT 7.23 PERCENT	5138000.	5357000.	5524000.	5690000.	5833000.

ESTIMATED TURN-ON COST= 64000.
ESTIMATED TURN-OFF COST= 64000.
INTEREST RATE= .0500

[a]75 MGD, MFS, single purpose plant.
See Appendix C for additional cost details.

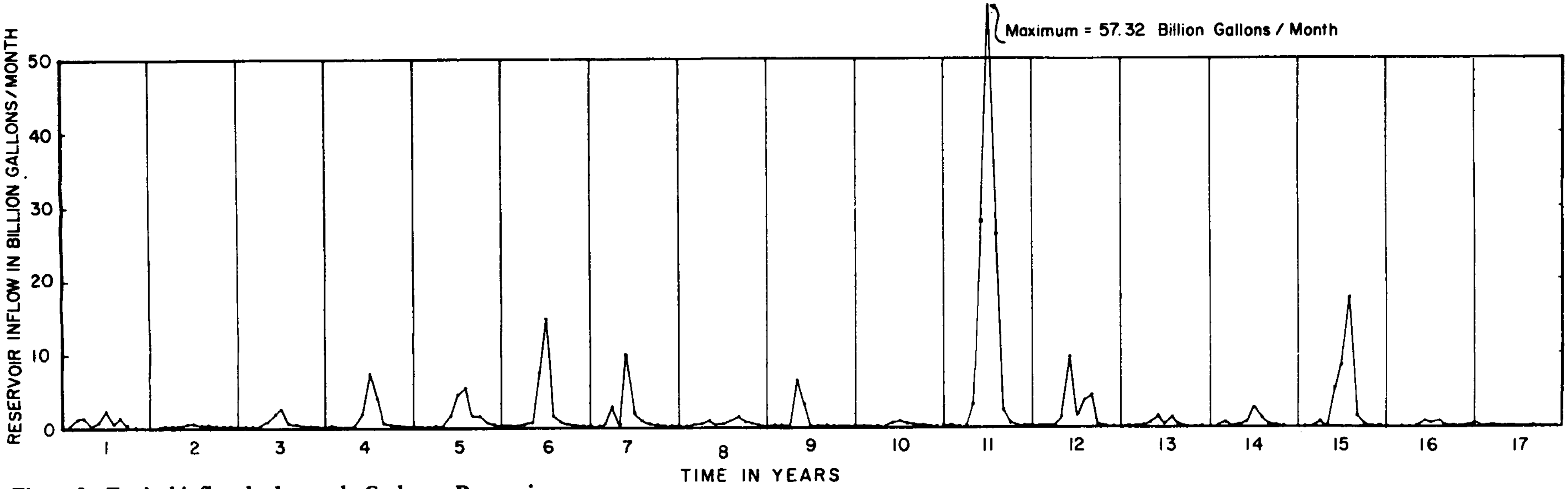

Figure 9. Typical inflow hydrograph, Cachuma Reservoir.

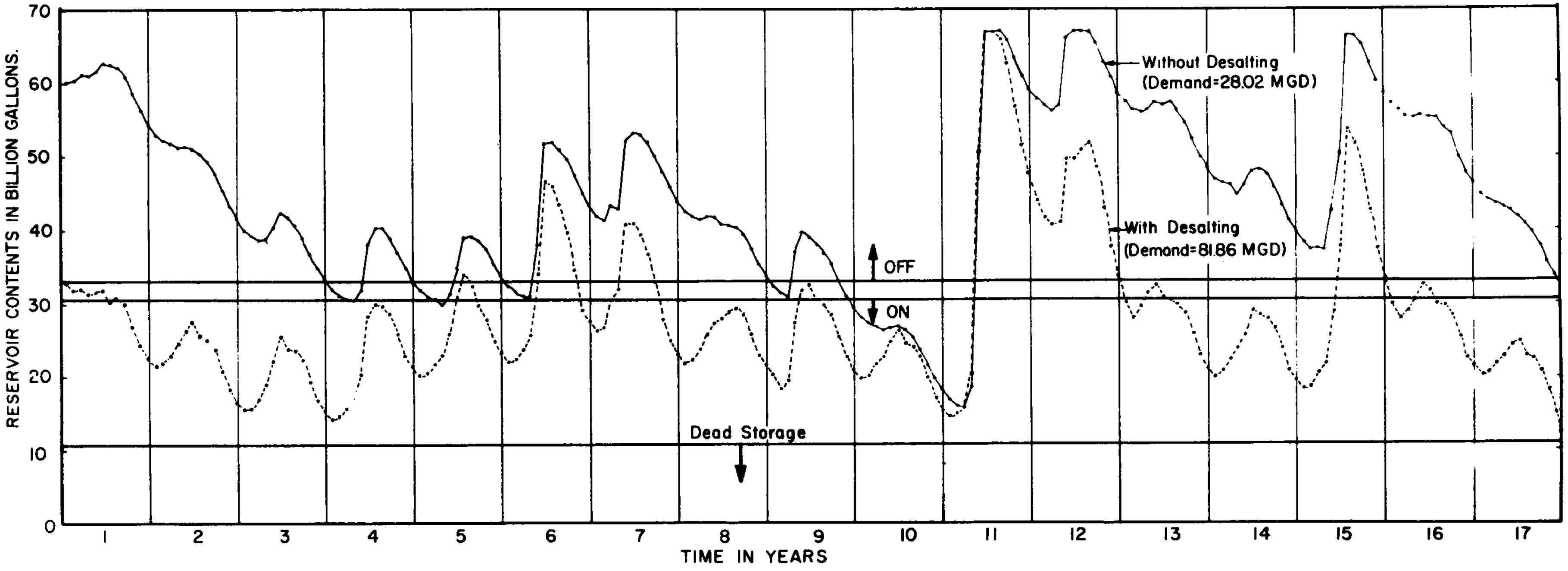

Figure 10. Cachuma Reservoir contents, with and without desalting.

produce more water than is needed, since the extra water is spilled and lost. Such rules can meet the demand but only at a higher cost. Thus the few rules left for final consideration are those that are the best among the many rules in the original set. Each of these few rules can efficiently produce the needed firm yield and often, as in this case, the differences among these better rules is slight.

The costs given above are the average of five separate simulation runs of 30 years each using different equally likely synthetic hydrographs of streamflow. The minimum cost for the best rule was the average of the following costs from simulation runs: $202,700, $181,700, $199,100, $200,700, and $203,300/year/MGD of added firm yield. This large range in costs for the optimum rule for the different equally likely streamflow sequences gives an indication of the variability of the hydrologic record.

A larger number of time periods would need to be used in the computation if a better estimate of the mean cost were needed, however for illustrating the operation of the program, the five periods of 30 years each were thought to be sufficient. In a real life application, the additional computer expense would probably be justified to secure a more precise value of the desalting costs, depending on the variability of streamflows involved.

For the 85 MGD plant, the optimum rule was ON at .22 and OFF at .20. The cost of water was $201,400/year-/MGD of added firm yield. For the 65 MGD plant, the optimum rule was ON at .80 and OFF at .95 and the cost was $214,600/year/MGD of added firm yield. Thus, the 75 MGD plant with optimum rule ON at .36 and OFF at .40 and a cost of $197,500 per year per MGD of added firm yield is the best of these three plants.

The average plant load factor was defined earlier as the average percent of time that the desalting plant runs in the years that it is turned on. Years with no desalted water production are not counted in the computation. This average plant load factor might be called a design load factor because it represents a mean probable service condition for the plant. The plant design is optimized for this operating point and the data used in cost computations are selected accordingly from the appropriate column in Fig. 8. In years that the plant operates only a short time, an economic penalty is paid because the plant is not operating at its optimum (design) load factor. The same is true when the plant runs more time in a year than its design load factor. In the Cachuma application load factors varied from 56 percent through 83 percent with the optimum 75 MGD plant running at 65 percent load factor.

To measure the efficiency of desalted water use in the system, a desalted water use/production ratio has been computed and is shown for each computation reported in Table 7. This measure of efficiency shows that portion of the desalted water production which is actually used in the system. Thus the ratio is the total desalted water production less any desalted water spills divided by total desalted water production. Since any desalted water overproduction is viewed as going over the spillway *first* when the reservoir is full, this definition of efficiency is quite severe with respect to the desalting plant operating rule. However, one should keep in mind that a perfect operating rule would spill no desalted water and the use/production ratio would be 1.0. In the Cachuma application for the optimum rule with the 75 MGD plant, the efficiency was 0.82. Thus most of the desalted water was actually used in the system. In other applications the efficiencies will be much lower.

Sensitivity Analysis for Cachuma Application

To help understand the Operating Rule Program and its use in planning for conjunctive operation of desalting plants, an effort was made to test the sensitivity of the computational results to changes in various input parameters. This series of computer applications was made on the Cachuma project data and comprises a "sensitivity analysis." Table 7 summarizes the results of this work. Each line of the table summarizes a whole series of computations by the Operating Rule Program. Line 2 represents the "basic" program results and all other lines should be compared with it. To minimize chance variations in the analysis, all runs were made with the same streamflow sequences. Sensitivity to the several input parameters is discussed in the following paragraphs.

Seasonal turn-on and turn-off increments

In the Operating Rule Program, there is provision to modify the operating rule each month according to whether the month usually has a low, average, or high streamflow as explained earlier. If a month is low, then no change is made in the rule. If the month is average, the turn-on level is decreased by the smaller increment given in the input and the turn-off level is also decreased by the same amount. If a month is high, then the turn-on and turn-off levels are decreased by the larger factor given in the input.

Line 6 of Table 7 shows the cost associated with changing the seasonal turn-on and turn-off increments as compared to line 2. Note that the increments of line 6 (0.05 and 0.10) are more efficient than in line 2 (0.25 and 0.05) and lead to the lower cost of $196,800/year/MGD. One could make still other changes in the increments to see if an even more efficient rule can be found.

Seasonal characterization

The program has three options for specifying the seasonal characterization of the monthly inflows. These are with three seasons (low average, and high), two seasons (low and high), or one season with all months the same.

Line 7 shows the summary of computations for a two season characterization (NSN=2) with a resulting cost of $197,900/year/MGD of added firm yield. Thus, the two season option performs almost as well as the three season option and is somewhat simpler.

Line 8 shows the results of a one season characterization (all months the same, NSN=1) with a resulting cost of $200,100/year/MGD. This option yields higher costs than the three season characterization of lines 2 or 6.

Operating costs

The cost data for the desalting plant must be supplied by the user of the Operating Rule Program. As noted before, for these application studies, cost data were furnished by the Oak Ridge National Laboratory under its contract with OSW, and were based on a MSF plant with 4 5/8 percent interest rate, 30 year plant life, fixed charge rate of 7.23 percent [1] and fuel at 35¢ per million BTU.

The results of the application studies depend a great deal on the cost input data used in the program. To illustrate, as shown in line 13, the costs increase to $221,700/year/MGD if the fixed charge rate remains at 7.23 percent, but the operating costs are increased 25 percent.

Reservoir size

Line 9 shows how reservoir size can change the cost. With the reservoir increased by 10 BG to 76.79 BG, the natural system can produce additional water by itself so the desalting plant production is decreased. This means a different rule (ON at .31, OFF at .30) is optimum and the unit cost of producing enough water to meet the same demand as before using the 75 MGD plant is slightly increased to $197,800/year/MGD. Since the required amount of desalted water production is smaller, however, the total cost of supplying the demand decreases from $10.88 million to $10.50 million per year when the reservoir is enlarged. Of course, the larger reservoir would cost more and this should be taken into account in comparing the alternatives. In this case it must be determined if $380,000 per year would pay for the enlargement of the reservoir.

Replacement life

In all applications up to this point, the replacement life of the desalting plant has been assumed to be 30 years. If the useful life were longer, then the capital investment would be spread over a longer period of time and even if annual operating costs remained the same, the cost of water would decrease. This effect is shown in line 12 and the cost decreases to $183,700/year/MGD with a replacement life of 50 years.

Demand coefficients

Some important input data are the demand coefficients which show the pattern of annual demand; i.e., what portion of the annual demand is needed each month of the year. Lines 10 and 11 show what happens if demand is assumed to be constant each month instead of distributed more in hot dry months as in all the other computations. The constant demand is more easily met by the system than a demand pattern with large needs occurring during low natural flows. The operating rule for a 75 MGD plant changes to ON at .26 and OFF at .25 with the cost being $192,300/year/MGD. The 65 MGD plant can now meet the smaller demand (the natural system produces more water) with a rule of ON at .61 and OFF at .70 with the cost being $201,000/year/MGD. Note that the smaller plant, however, produces the water at a higher cost and runs at a higher load factor.

Definition of firm yield

In all the cases described to this point the firm yield was defined at 95 percent probability. That is, the demand was to be met 95 years out of 100. Lines 4 and 5 illustrate the effects of changing the probability associated with firm yield. If firm yield is defined at 90 percent as in line 5, then the natural system can, of course, meet a larger part of the demand. Thus, the optimum operating rule changes to ON at .30 and OFF at .30 while the additional firm yield that is needed decreases to 51.83 BG. This smaller production from the same plant yields a higher annual unit cost of $207,400/year/MGD of additional firm yield. A smaller plant would be able to meet the smaller desalting demand more economically and this option should be investigated.

The data in line 4 are for a 99 percent firm yield specification. Now the natural system is less capable of meeting the water requirements and the desalting plant must produce more. The larger production costs of the desalted water are now spread over an even bigger increase in firm yield thus giving a smaller unit cost of $195,100/year/MGD. To properly understand the cost variation as the definition of firm yield is changed, one should look at average annual costs of meeting the demand rather than at the unitized costs per MGD. The average annual costs for 90, 95, and 99 percent firm yields are $10,760,000, $11,029,000 and $11,517,000 respectively. Thus, the more relaxed the definition of firm yield, the lower the total cost, while the highest unitized cost occurs with the 90 percent definition.

Lines 14 and 15 illustrate the wasteful nature of base load operation of the desalting plant. Assuming the smallest possible (65 MGD) plant is designed for base load operation and is operated 90 percent of the time (10

[1] The fixed charge includes depreciation and other costs of capital as well as interest.

percent required for maintenance), then the cost of supplying the needed water with base load operation is \$226,200/year/MGD of added firm yield. If the optimal 75 MGD plant is run 90 percent of the time, the added firm yield would cost \$259,300/year/MGD. The economic advantage of conjunctive operation is readily seen.

The Salt Lake-Deer Creek Application

Purpose

The purpose of this application study is to find the lowest cost conjunctive operation desalting alternative to increase the firm yield of the Deer Creek Project to 220 MGD with reservoir size held constant. The cost of supplying the increased firm yield, the optimum size plant, and the associated optimum operating rule are to be determined

System description

Five streams presently supply about 70 percent of Salt Lake City's more than 22 billion gallons yearly water requirement–City Creek, Parley's Creek, Big Cottonwood Creek, Little Cottonwood Creek, and Emigration Springs. An additional 12 percent of the water requirement is obtained from 100 flowing wells located in the Murray Artesian Basin area, about 7 miles southeast of the city and from several large pumped wells located along the north and east bench area of the city. Most of these pumps are operated from a remotely controlled telemetering center where flow records are automatically recorded. Some of the larger pumped wells are equipped with automatic variable speed pumps which keep the quantity of water pumped equal to the varying demand.

The remaining 18 percent of the city's annual water requirement is supplied by the Deer Creek Project which was completed by the U.S. Bureau of Reclamation in 1952. Deer Creek Reservoir, located about 40 miles southeast of Salt Lake City in Provo Canyon, adds water to the city distribution system through a 69-inch diameter concrete pipeline.

The percentages mentioned above may vary considerably from year to year depending upon the amount of water available in the streams. For example, the amount of water supplied from the five streams has been as little as 55 percent or as high as 90 percent, with corresponding adjustments in the amounts supplied from wells and from the Deer Creek system. The amounts supplied from the Deer Creek system have varied from about 5 percent to 28 percent. This percentage may be expected to increase continually as the city grows since the capacity of the Deer Creek system has not been reached yet. Treatment facilities for this water are located near Salt Lake City in the mouth of Little Cottonwood Canyon. The Deer Creek Project also meets some agricultural water requirements in Utah Valley.

The Salt Lake-Deer Creek application model simulates the operation of the Deer Creek system in conjunction with a desalting plant. The model includes both demands for municipal and industrial water and for agricultural water. The municipal and industrial water flows through the Deer Creek-Salt Lake Aqueduct to the Salt Lake City metropolitan area. The agricultural demands are represented by all other releases from the reservoir, some of which are releases during non-irrigation and flood seasons, to downstream storage.

While Salt Lake City is in a semi-arid area with an average annual precipitation of about 16 inches, the high mountains nearby, from which the streams flows, receive up to 60 inches of annual precipitation at high elevation.

Input data and results

Basic data available for the model were taken from many sources and consist of records of storage levels on Deer Creek Reservoir, records of flows in the Salt Lake Aqueduct, records of streamflow, and records of releases from storage for agricultural demands. No direct reservoir inflow data are available as much of the reservoir inflows consists of flows from several small ungaged streams. A partial record of evaporation at the reservoir is also available. A U.S. Bureau of Reclamation area-capacity curve is available for the reservoir and appears as Table 8.

Evaporation data for the reservoir were estimated by correlating basic climatological data with the partial record of evaporation which is available. The evaporation potential is given in Table 9.

Water requirements in the model for municipal and industrial use and for agricultural use were based upon the records of past deliveries for these uses.

The reservoir inflow record in Table 10 was estimated by adjusting total outflow records for storage changes and evaporation losses.

The Deer Creek project with its 49.78 BG storage represents most of the storage available in the Salt Lake City water system. Except for small regulating and equalizing reservoirs, the only other storage is the small Mountain Dell Reservoir. In general, Salt Lake City uses all the water possible from other sources, as limited by physical and legal requirements, and then supplies the balance of its needs with Deer Creek project water.

The Salt Lake-Deer Creek application model assumes that a desalting plant could be built northwest of the city to reclaim the brackish water, sewage effluent, and Jordon River return flow before these waters enter the Great Salt Lake. The desalted water would be pumped into existing regulating and equalizing reservoirs for mixing before use. Desalted water production would thus hold the water upstream in the Deer Creek Reservoir.

Table 8. Elevation-capacity data.

DEER CREEK RESERVOIR

Water surface elev. in feet	Capacity of res. in ac-ft
5290.	0.
5295.	1000.
5300.	2000.
5305.	3000.
5310.	4542.
5315.	6532.
5320.	8999.
5325.	11983.
5330.	15429.
5335.	19266.
5340.	23495.
5345.	28128.
5350.	33244.
5355.	38911.
5360.	45172.
5365.	51949.
5370.	59102.
5375.	66663.
5380.	74653.
5385.	83177.
5390.	92272.
5395.	101902.
5400.	112148.
5405.	123087.
5410.	134761.
5415.	147396.
5417.	152750.

Desalted water production not immediately used would be stored indirectly in Deer Creek Reservoir by reducing the need for deliveries from that project. If necessary, desalted water could be pumped back upstream for storage at added cost.

Thus, in this Salt Lake-Deer Creek application of the Operating Rule Program, only the operation of part of the Salt Lake City water system has been studied while assuming that the city will continue to draw all it can from its other sources with future water deficits to be supplied by a desalting plant.

The demand used in the study is the total projected demand on the Deer Creek project for all uses including present irrigation rights and present plus future municipal and industrial needs.

Table 9. Monthly evaporation potential, Deer Creek Reservoir.

Month	Evaporation (Inches)
Oct.	3.18
Nov.	1.17
Dec.	.57
Jan.	.49
Feb.	.81
Mar.	2.12
April	3.99
May	6.39
June	8.18
July	10.33
Aug.	9.06
Sept.	5.89

The approach used in this application illustrates one way of analyzing a complex system; that is, by separating out the major storage reservoir for operation with the desalting plant.

Fig. 11 shows a typical page of general input used in the computer computations for Deer Creek. Fig. 12 shows the cost data used in the computations for the 65 MGD plant. Table 11 summarizes results of the series of computations.

Three sizes of plants, 50, 65, and 75 MGD, were studied for the Deer Creek application of the program. The 65 MGD plant was the most economical of the three and produced the necessary added firm yield at a uniform annual cost of $183,400/year/MGD while operating with a rule of ON at .46 and OFF at .80. The average plant load factor was 59 percent and the desalted water use/production ratio was 0.75. Thus the Deer Creek plant operated at a slightly smaller load factor and efficiency than the Cachuma plant.

Line 1 of Table 11 is of particular interest because it shows a rule of ON at .98 and OFF at .98. This rule gives approximately the smallest possible conjunctively operated plant.. While the plant of line 1 shows a distinct advantage over the base load operations of lines 4 and 5, it still is a more costly rule and plant size than the optimal plant of line 2. This is because the plant of line 1 wastes more desalted water over the spillway as shown by its lower efficiency of 0.55.

No further sensitivity analysis runs were made for the Deer Creek study since the plant size and other results were similar in range to the Cachuma study.

Table 10. Computed inflows to Deer Creek Reservoir in ac-ft.

YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT
1921	157	181	168	158	137	310	340	685	1014	208	181	169
1922	1480	1720	2320	1810	1600	2290	3500	9260	6970	1960	2010	1560
1923	1400	1960	2060	1770	1490	1970	4550	9070	5460	2310	1840	1570
1924	1860	1720	1770	1520	1650	1670	1960	2690	1170	850	860	690
1925	820	1230	1150	1140	1230	1770	1260	2600	2070	1390	1190	1280
1926	1320	1360	1380	1100	1120	2000	3000	3750	1630	990	1060	820
1927	1070	1320	1480	1120	1260	2200	3600	5700	4130	1900	1410	1290
1928	1430	2270	1930	1720	1470	2600	2320	6850	2890	1560	1180	410
1929	1160	1490	1470	1370	1200	2200	2470	4440	4280	1630	1570	1610
1930	1410	1580	1770	1550	1570	1780	2100	2360	2420	1270	1240	1140
1931	1660	1510	1510	1400	1230	1320	850	1230	750	500	490	420
1932	540	850	970	980	1250	1890	2440	4880	4790	1620	1280	1000
1933	910	1110	1200	1320	1020	1740	1580	2010	4120	1210	850	620
1934	710	880	870	1070	1040	1040	620	650	460	350	370	370
1935	370	620	810	1010	950	1020	930	2430	4710	1190	890	700
1936	770	950	860	1080	1100	1630	3900	6600	3110	1660	1170	900
1937	990	1360	1220	1210	1260	1930	2680	5800	2860	1610	1300	970
1938	1150	1360	1450	1260	1200	2300	3000	4920	3530	1790	1220	1070
1939	1210	1490	1430	1260	1130	2190	2100	2900	1900	960	810	720
1940	1050	980	920	1220	1250	1300	1030	2700	1360	830	630	630
1941	730	930	970	1100	1110	1590	1159	3461	2821	1681	1393	1140
1942	976	1095	1532	1531	1241	1465	2754	3254	3474	1815	1398	938
1943	834	856	1083	1395	1604	2113	3638	3803	3737	2046	1857	1661
1944	1024	1121	1355	1421	1175	1260	1480	4070	5050	2290	2077	1600
1945	974	990	848	1366	1350	2189	1620	4600	3720	2464	2230	2000
1946	1239	1349	1631	1615	1380	1635	1720	3087	2892	2734	2242	1817
1947	1090	1403	2879	2705	1534	1985	2723	3828	2858	2650	2243	1790
1948	1180	1295	1487	1430	1365	459	1350	3929	2923	2420	2150	1610
1949	811	1141	1710	1711	1405	1741	2095	3712	5046	2997	2370	1917
1950	1360	1460	1330	1670	1490	1770	2010	4090	5880	2890	2390	2030
1951	1310	1118	1717	1749	1600	1840	2237	3975	4720	3012	2378	2298
1952	1597	1644	1810	1776	1637	1767	5070	9790	6164	3120	2375	2580
1953	2139	1670	1865	1730	1360	1890	1710	2585	7515	1330	1160	1010
1954	1115	1560	1596	1659	1557	1628	2410	4520	1550	1151	879	827
1955	927	1403	1381	1399	1207	1740	2011	6011	4580	1320	1112	981
1956	1165	1660	2410	2116	1671	2159	3548	9458	5625	1370	1115	844
1957	975	1420	1579	1626	1678	1733	1907	6355	7450	3100	465	1200
1958	1581	1820	1600	1374	1459	1343	3062	9600	4920	1212	1028	942
1959	1070	1433	1485	1427	1411	1724	1854	3839	4662	1212	780	903
1960	1569	1514	1311	1268	1183	1929	2487	4937	3415	978	682	657
1961	878	1285	1253	1150	1030	1340	870	2618	1226	498	497	930
1962	1290	1554	1526	1422	2498	1888	6470	8357	10600	1960	1180	920
1963	1130	1033	1177	1240	1995	1325	2100	6606	6217	1460	890	1000
1964	1018	1373	1575	1205	918	1213	2180	8155	9412	2453	1319	896
1965	919	1452	1990	1606	1484	1420	3140	8706	10380	5767	2338	1884

Figure 11. Input data, Salt Lake-Deer Creek application.

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     DEER CREEK APPLICATION WITH A 65 M.G.D. DESALTING PLANT

NO.OF PERIODS IN SIMULATION=  5          NO. OF YEARS IN EACH PERIOD=  30
NO.OF PERIODS IN FIRM YIELD=  5          NO.OF YEARS IN EACH PERIOD=  75

NPRC= 27
CMAX= 49.780 B.G.
CMIN=   .978 B.G.
OSCAP= 65.00 M.G.D.
FORCE= 1
KIO= 1
KPC= 2
KIP= 2
KREAD= 1
IFLOW= 3
ISTOR= 1
IYEAR= 1
KIK= 1

THERE ARE  1 DEMAND LEVELS IN THIS RUN AS FOLLOWS
      220.0

DEMB= 217.000 M.G.D.
RBAR=    .000 M.G.D.


THIS IS A 3 SEASON RUN
AVE. SEASON ON INC= .025          AVE. SEASON OFF INC= .025
WET SEASON ON INC.= .050          WET SEASON OFF INC.= .050
```

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT
MONTHLY SEASON ASSIGNMENT	1	2	2	2	2	2	3	3	3	2	2	1
DEMAND COEFFICIENTS	.64	.58	.62	.76	1.09	1.39	1.83	1.66	1.23	.89	.66	.65
RELEASE COEFFICIENTS	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00

```
TURN-ON FRACTIONS      .50  .40
TURN-OFF FRACTIONS     .80

START= .75
STEP= .05
PCF= .99
```

Figure 12. Cost data, Salt Lake-Deer Creek application.[a]

COST DATA FOR DESALTING PLANT USED IN ANALYSIS

OPER. L. F. (IN PERCENT)	ANNUAL COST IN $/YR. FOR THE PLANT THAT IS OPTIMIZED AT THE GIVEN LOAD FACTOR (IN PERCENT)				
	50.	60.	70.	80.	90.
0.	31500.	31500.	31500.	31500.	31500.
10.	1036000.	1004000.	971000.	959000.	946000.
20.	1926000.	1870000.	1814000.	1786000.	1758000.
30.	2813000.	2732000.	2653000.	2610000.	2567000.
50.	4592000.	4464000.	4336000.	4258000.	4179000.
70.	6371000.	6208000.	6045000.	5928000.	5811000.
90.	8101000.	7876000.	7651000.	7517000.	7383000.
100.	8996000.	8730000.	8484000.	8327000.	8193000.
ANNUAL FIXED CHG. AT 7.23 PERCENT	4720000.	4860000.	5000000.	5130000.	5260000.

ESTIMATED TURN-ON COST= 55000.
ESTIMATED TURN-OFF COST= 55000.
INTEREST RATE= .0500

[a]65 MGD, MFS, single purpose plant.

See Appendix C for additional cost details.

Table 11. Summary of cost computations, Salt Lake-Deer Creek application.

Line No.	Probability level defining firm yield %	Demand MGD	Firm yield without desalting MGD	Required increase in firm yield MGD	Plant size MGD	Optimum rule (reservoir fraction full) ON	OFF	Average plant load factor %	Desalted water use/production ratio (efficiency)	Number of feasible rules tried	Average levelized cost in $/yr per MGD of added firm yield
1	99	220	176.8	43.2	50	0.98	0.98	68	0.55	1	197,400
2	99	220	176.8	43.2	65	.46	.80	59	0.75	4	183,400
3	99	220	176.8	43.2	75	.48	.60	48	0.77	5	193,300
4	99	220	176.8	43.2	65	Base Load		90	-	-	294,900
5	99	220	176.8	43.2	50	Base Load		90	-	-	230,600

For other conditions of the computations see Figs. 11 and 12.

Useful plant life = 30 years

New York City Application

Purpose

The purpose of this application study is to find the lowest cost conjunctive operation desalting alternative to increase the firm yield of the New York system to 1970 MGD with reservoir size held constant. The cost of supplying the increased firm yield, the optimum plant size, and the associated optimum operating rule are to be determined.

New York City was selected for study as an example of how the program might be used for analysis of a very large metropolitan system in a humid area. The hydrologic data was crudely adapted from studies made for other purposes. The cost data were extrapolated from studies made for smaller plants. The study is intended only as an example, and without further refinement the numbers generated do not necessarily have relevance to the application of desalting to meet the future needs of the city.

System description

In the New York City application, a different approach was used from that applied in the Salt Lake-Deer Creek study. Here the entire system was lumped together and operated as a whole. This means that all the storage of the system was added together and considered as one storage reservoir with average characteristics similar to the east branch of the Ashokan Reservoir. All of the watershed runoffs tributary to the system were also added together to give one composite record of natural inflow to the system. The desalting plant or plants could be located in the most economical location for production, distribution, and availability of a salt water supply. The assumption is made that the system has sufficient controls so all reservoirs can be made to fluctuate up and down together and that desalted water production is backed up proportionately into all reservoirs.

The following description of the New York City system is taken from OSW Research and Development Progress Report No. 207 (1966) pages 3-9 through 3-11. The major facilities constituting the supply system are shown in Fig. 13 which was furnished by the Board of Water Supply of the City of New York.

> New York City draws practically its entire water supply from three surface water sources, which are the Croton, Catskill and Delaware Systems. In addition to New York City, these sources supply, wholly or partially, areas of Elmsford, Mount Vernon, New Castle, New Rochelle, North Tarrytown, Ossining, Peekskill, Pleasantville, Scarsdale, Tarrytown, White Plains and Yonkers. The total system serves a population of approximately 8.5 million people. Current normal use, with an ample supply, would probably approach 1.3 BGD....
>
> System descriptions and percentages of supply are as follows:
>
> *Catskill*—Forty-three percent of the 1961 supply was from this source. Schoharie Creek is impounded in Schoharie Reservoir, and the water is carried by Shandaken Tunnel to Esopus Creek, which is impounded in Ashokan Reservoir. The mixed water is conveyed to Kensico Reservoir by the Catskill Aqueduct. A small amount of water is supplied to consumers directly from the aqueduct before it reaches Kensico Reservoir.
>
> *Delaware*—This source furnished thirty-six percent of the 1961 supply. East Branch Delaware River is impounded in Pepacton Reservoir, and the Neversink River is impounded in Neversink Reservoir. The water

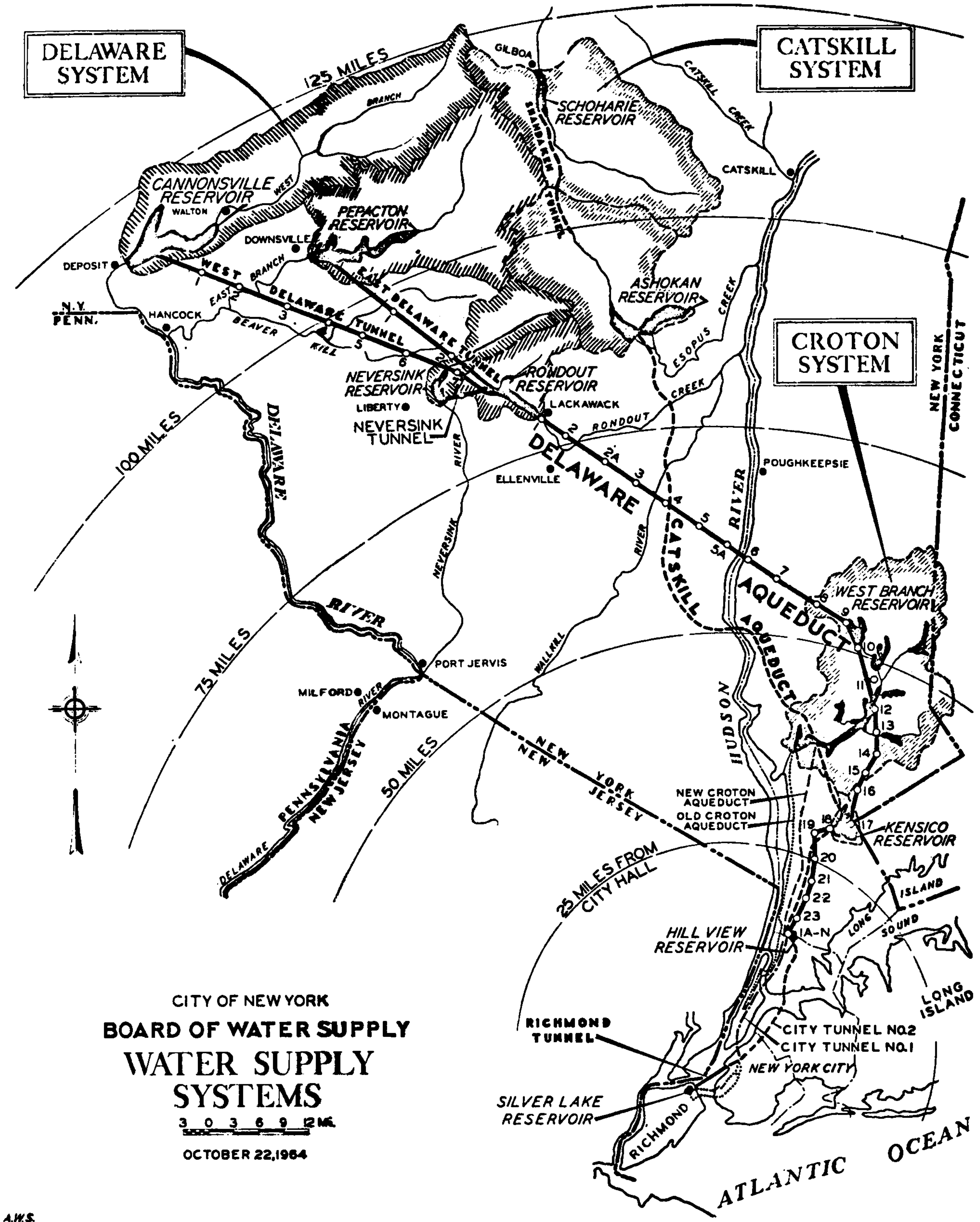

Figure 13. Water systems, New York City and Northern New Jersey.

of these two reservoirs is carried to Rondout Creek which is impounded in Rondout Reservoir. Water from Rondout Reservoir is transported by the Delaware Aqueduct to the West Branch (Croton) Reservoir and then into Kensico Reservoir.

Croton—Eighteen percent of the 1961 supply came from this source. Waters from Rondout Reservoir, Boyd Corners Reservoirs, and other related tributary sources mix in West Branch (Croton) Reservoir. Part of the mixed water is carried to the Rye Lake area of Kensico Reservoir. Some water from Middle Branch and Cross River Reservoirs is carried to Kensico Reservoir. The New Croton Reservoir is formed by waters of the Croton River Basin and the Delaware Aqueduct. Water from the New Croton Reservoir serves areas in Manhattan and the Bronx as well as other communities. Kensico Reservoir receives water from the Bronx River Basin, which mingles with water from the Catskill, Delaware, and Croton Rivers. From Kensico, these mixed waters flow through the Catskill and Delaware Aqueducts to Hillview Reservoir, supplying several communities enroute. Water from Hillview is delivered to the five New York boroughs and some adjacent communities.

The Cannonsville Reservoir was added to the above system in 1966. The total storage in all the impounding and storage reservoirs and not counting distribution reservoirs and standpipes comes to a little over 603 billion gallons.

Input data

Watershed runoff records for the entire lumped system are given on page 11-5 of OSW Report 207 (1966) and are shown as Table 12. Note that 1965 is the last year given. The mid-1960 drought continued into 1968. If the three additional dry years had been available, the streamflow simulator would have reflected this condition by generating more severe droughts in the synthetic hydrographs. This, in turn, would have required more desalted water production.

Table 12. Inflow to New York system in billion gallons.

YEAR	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
1929	57	46	229	248	130	33	9	14	7	48	59	80
1930	94	64	142	84	38	68	10	6	12	1	11	17
1931	17	31	4	201	138	58	88	19	17	2	11	46
1932	121	96	64	186	67	47	14	12	0	115	165	46
1933	59	43	135	213	58	19	5	136	104	40	42	57
1934	90	26	124	142	102	24	19	17	72	56	78	112
1935	106	44	148	106	80	27	99	14	12	19	14	59
1936	70	29	409	152	36	23	6	12	14	21	60	110
1937	174	97	71	162	130	64	36	48	65	107	94	86
1938	100	80	82	80	67	63	120	86	162	33	63	150
1939	62	121	141	154	35	22	7	7	0	31	51	41
1940	36	35	110	335	137	60	26	11	23	12	55	95
1941	68	57	59	138	38	22	22	17	1	1	25	65
1942	57	48	180	105	91	44	19	29	54	63	99	128
1943	80	98	170	128	182	76	11	13	0	36	102	27
1944	25	35	125	148	68	25	9	12	27	19	38	86
1945	78	64	278	98	157	85	117	46	59	76	100	90
1946	110	58	40	38	126	97	25	20	17	24	28	30
1947	98	50	32	180	170	72	45	21	14	13	90	40
1948	23	69	283	152	118	74	27	13	1	11	48	120
1949	166	105	95	85	92	14	7	12	12	9	28	86
1950	106	62	132	180	80	60	35	33	22	13	120	167
1951	117	143	161	182	56	34	52	18	14	46	48	134
1952	130	90	140	205	105	78	53	27	25	12	55	146
1953	129	103	202	140	118	19	7	6	14	8	38	115
1954	55	112	110	95	133	28	7	6	25	22	137	113
1955	54	64	164	110	40	34	7	157	19	293	160	38
1956	45	57	132	292	96	40	25	7	23	27	54	109
1957	69	51	80	141	81	15	7	6	1	7	32	175
1958	80	46	178	251	223	37	20	8	16	46	97	54
1959	84	60	92	168	40	18	6	6	6	102	142	148
1960	94	108	87	203	84	56	34	23	123	34	43	45
1961	23	128	153	189	115	58	16	21	9	6	20	29
1962	89	30	122	193	51	18	6	6	1	20	61	72
1963	26	24	174	108	40	36	18	17	6	6	58	55
1964	119	61	191	143	47	27	1	0	0	2	10	31
1965	37	101	49	135	60	22	6	11	15	8	20	40

The New York City system is required to make certain mandatory releases on some streams for pollution control and to fulfill certain court decrees. These releases fluctuate widely from year to year making estimation of the mean releases difficult. Examination of certain published data indicate that the required mean releases lie between 150 and 300 MGD depending on climatic conditions. For most of the computations described below, 150 MGD mandatory releases were assumed. The assumed composite reservoir capacity data are shown in Table 13. Evaporation potential for the New York application is given in Table 14. Other typical input conditions for the series of computations are summarized in Fig. 14 while Fig. 15 shows the cost data for the 250 MGD plant.

Results

The results of the New York City system studies are summarized in Table 15. Two groups of computations were made, one with firm yield defined at 99 percent probability and the other at 95 percent. The results are discussed in the same order.

Table 13. Elevation-capacity data.

NEW YORK CITY WATER SYSTEM

Reference elev. in feet	Total cap. of all res. in billion of gal.
440.	0.
460.	3.
480.	12.
500.	20.
505.	22.
510.	26.
515.	36.
520.	49.
525.	66.
530.	85.
535.	109.
540.	135.
545.	163.
550.	193.
555.	225.
560.	260.
565.	298.
570.	337.
575.	379.
580.	424.
585.	471.
590.	520.
595.	571.
600.	624

Table 14. Monthly evaporation potential, New York Reservoir.

Month	Evaporation (Inches)
Jan.	1.0
Feb.	2.0
Mar.	2.0
April	3.0
May	4.0
June	5.0
July	5.0
Aug.	4.0
Sept.	3.0
Oct.	2.0
Nov.	1.0
Dec.	1.0

Firm yield at 99 percent

Preliminary information from the firm yield part of the program indicated the firm yield without desalting is 1759.6 MGD. This means that with a demand of 1970.0 MGD, the required increase in firm yield is 210.4 MGD. Past experience with the program has shown desalting plant capacity 1.30 times the firm yield increase is advisable for initial computer analysis. Thus the first size studied was 275 MGD. Then other plant capacities were assumed and a series of computations made until plant sizes of 210, 225, 250, 275, and 300 had been studied. The optimum plant size based on the selected inputs was found to be 250 MGD operating with a rule of ON at .77 and OFF at .70, and with a cost of $145,200/year/MGD of added firm yield as shown in line 3 of Table 15.

The optimal 250 MGD plant operates at a load factor of 51 percent. The efficiency (.24) is surprisingly low. This value means that only 24 percent of the desalted water production actually is used. The rest escapes over the spillway and is lost. The reader will recall that the desalted water use/production ratio (efficiency) for Cachuma and Deer Creek applications were .82 and .75 respectively. Why should the New York City system apparently waste so much desalted water production?

In the first place one should keep in mind that in spite of the apparent wastefulness of the operating rule, the necessary increase in firm yield has been added to the system by the desalting plant. The water supply has been available when needed to prevent shortages. The critical low flow periods have been filled in with desalted water. The so called efficiency is low because in the New York system, the desalting plant only furnishes about 10.7 percent of the demand. The natural inflow of the system is so large compared to the desalted water production that

Figure 14. Input data, New York City application.

```
  NEW YORK APPLICATION ------ 250 M.G.D. MSF DESALTING PLANT

NO.OF PERIODS IN SIMULATION=  5          NO. OF YEARS IN EACH PERIOD=  30
NO.OF PERIODS IN FIRM YIELD=  5          NO.OF YEARS IN EACH PERIOD=  75

NPRC= 24
CMAX=623.574 B.G.
CMIN= 20.000 B.G.
DSCAP=250.00 M.G.D.
FORCE= 1
KIO= 1
KPC= 2
KIP= 2
KREAD= 1
IFLOW= 4
ISTOR= 2
IYEAR= 2
KIK= 1

THERE ARE  1 DEMAND LEVELS IN THIS RUN AS FOLLOWS
      1970.0

DEMB=2350.000 M.G.D.
RBAR= 150.000 M.G.D.


THIS IS A 3 SEASON RUN
AVE. SEASON ON INC= .050          AVE. SEASON OFF INC= .050
WET SEASON ON INC.= .100          WET SEASON OFF INC.= .100
```

	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
MONTHLY SEASON ASSIGNMENT	2	2	3	3	2	1	1	1	1	1	2	2
DEMAND COEFFICIENTS	.92	.90	.92	.95	1.00	1.06	1.08	1.10	1.10	1.05	1.00	.92
RELEASE COEFFICIENTS	.30	.30	.30	.50	.60	1.00	1.50	2.50	2.50	1.80	.40	.30

```
TURN-ON FRACTIONS        .80  .70
TURN-OFF FRACTIONS       .70

START= .75
STEP= .05
PCF=1.00
```

Figure 15. Cost data, New York City application.[a]

COST DATA FOR DESALTING PLANT USED IN ANALYSIS

OPER. L. F. (IN PERCENT)	ANNUAL COST IN $/YR. FOR THE PLANT THAT IS OPTIMIZED AT THE GIVEN LOAD FACTOR (IN PERCENT)				
	40.	50.	60.	70.	80.
0.	115000.	115000.	115000.	115000.	115000.
10.	3645000.	3496000.	3370000.	3245000.	3225000.
20.	6870000.	6562000.	6360000.	6157000.	6084000.
30.	10095000.	9628000.	9347000.	9067000.	8940000.
50.	16542000.	15757000.	15323000.	14886000.	14617000.
70.	22985000.	21887000.	21293000.	20700000.	20367000.
90.	29265000.	27846000.	27096000.	26347000.	25907000.
100.	32439000.	31013000.	30040000.	29222000.	28667000.
ANNUAL FIXED CHG. AT 7.23 PERCENT	15244000.	15907000.	16440000.	16972000.	17358000.

ESTIMATED TURN-ON COST= 200000.
ESTIMATED TURN-OFF COST= 200000.
INTEREST RATE= .0500

[a] 250 MGD, MFS, single purpose plant.

See Appendix C for additional cost details.

Table 15. Summary of cost computations, New York City application.

Line No.	Probability level defining firm yield %	Demand MGD	Firm yield without desalting MGD	Required increase in firm yield MGD	Plant size MGD	Optimum rule (reservoir fraction full) ON	OFF	Average plant load factor %	Desalted water use/production ratio (efficiency)	Number of feasible rules tried	Average levelized cost in $/yr per MGD of added firm yield
1	99	1970.0	1759.6	210.4	210	99	99	78	0.18	1	161,600
2	99	1970.0	1759.6	210.4	225	90	90	68	0.19	2	160,700
3	99	1970.0	1759.6	210.4	250	77	70	51	0.24	5	145,200
4	99	1970.0	1759.6	210.4	275	74	70	48	0.24	5	156,100
5	99	1970.0	1759.6	210.4	300	72	70	46	0.24	4	163,400
6	99	1970.0	1759.6	210.4	250	Base Load		90	-	-	207,800
7	99	1970.0	1759.6	210.4	210	Base Load		90	-	-	175,500
8	95	1970.0	1856.2	113.8	110	98	98	81	0.20	1	165,600
9	95	1970.0	1856.2	113.8	125	82	85	68	0.22	3	169,600
10	95	1970.0	1856.2	113.8	150	60	80	57	0.30	4	164,200
11 [a]	95	1970.0	1856.2	113.8	150	80	80	65	0.23	1	191,400
12	95	1970.0	1856.2	113.8	175	58	60	48	0.32	6	166,500
13	95	1970.0	1856.2	113.8	200	50	50	44	0.34	4	169,400
14	95	1970.0	1856.2	113.8	150	Base Load		90			242,400
15	95	1970.0	1856.2	113.8	110	Base Load		90			174,700
16	100	1970.0	1720.0	250.0	Mandatory releases = 150 MGD						
17	100	1970.0	1558.0	412.0	Mandatory releases = 296.5 MGD						

For other conditions of the computation, see Figs. 14 and 15 and below.
Useful plant life = 30 years
Reservoir capacity = 603.57 BG

[a]Computation done off optimum to show the effect of using a bad operating rule.

the rise and fall of the reservoir contents depend mostly on the natural inflow and not much on the desalting plant. When wet weather comes with high flows, the reservoirs fill quickly and desalted water production from preceding months may be wasted along with natural spills.

On the other hand, in a system such as Cachuma, where desalted water furnishes 69.8 percent of the demand, the reservoir contents depend more on the desalting plant than on the natural flows except in cases of unusual floods. Thus the operating rule controls the reservoir storage to a greater extent and the operating rule is able to minimize waste of desalted water production by shutting the plant off ahead of spillage.

Line 1 of Table 15 shows the smallest plant size (210 MGD) that can meet the demand. The operating rule is ON at .99 and OFF at .99 and the associated cost is $161,600/year/MGD. Lines 6 and 7 show base load operation costs to be $207,800/year/MGD for the 250 MGD plant and $175,500/year/MGD for the 210 MGD plant.

Firm yield at 95 percent

Lines 8 through 14 show results of computations with firm yield defined at 95 percent. Plant sizes from 110 to 200 MGD were studied. Since more shortages are tolerated under this definition, the natural system can supply more of the demand and the desalting plant only has to produce an increase of 113.8 MGD. Note that a 110 MGD plant is able to supply the 113.8 MGD increase in firm yield. This apparent paradox is possible because some shortages are allowed. The optimal size plant is 150 MGD operating with a rule of ON at .60 and OFF at .80 with a cost of $164,200/year/MGD of added firm yield as shown in line 10.

The optimal size plant operates at a design load factor of 57 percent. The efficiency is .30 which is somewhat better than the 99 percent firm yield case discussed earlier.

Line 11 shows the consequence of operating with a poor rule. The computer program was constrained to run with the non-optimal rule of ON at .80 and OFF at .80. The associated cost increased to $191,400/year/MGD. Line 14 shows the base load operation of a 150 MGD plant to cost $242,400/year/MGD, while a 110 MGD base load plant shown in line 15 would produce the added firm yield for $174,700/year/MGD.

If the firm yield is defined at 100 percent probability as line 16 of Table 15, then the yield without desalting drops to 1720 MGD. If, in addition, mandatory releases are assumed to be 296.5 MGD as in line 17, then firm yield without desalting decreases to 1558 MGD. If the additional drought years had been used as part of the hydrologic input, the results would indicate a still lower firm yield without desalting. This points up the urgent need for additional supplies in the New York City system for drought insurance in the future as the demand increases beyond the present value.

General Comments on the Applications

Uncertainty in input data

In the previous paragraphs the effect of arbitrarily changing various input parameters has been discussed. One question remains unanswered, however, concerning the input data. How much does error or uncertainty in the input affect the operation and economics of the desalting plant? The question has been partially answered since the sensitivity of the optimum operating rule and the cost of added firm yield to changes in input have been shown. But suppose the historical hydrologic record is either very short or not known with much accuracy. This uncertainty about the hydrology would be reflected by a corresponding uncertainty in the results. If dry spells were not as severe in the record as might eventually occur, then the synthetic streamflow sequences would not contain the resulting severe droughts and the program would not, of course, simulate operation of the plant under those severe conditions. In this respect, the results are subjected to some limitations as any other hydrological design problem under the same circumstances. If no record of inflow to the reservoir exists, a record estimated from the records of nearby streams would serve better than none at all; these might be quite good if the area is hydrologically homogeneous with strong correlation between the flows of different streams.

Another important question concerns the adequacy of the streamflow generator in reconstructing equally-likely hydrographs. This question is discussed in a separate report which is included as Appendix B "Evaluation of the Adequacy of Streamflow Operational Hydrology" by Roland W. Jeppson and Calvin G. Clyde.

Effect of conjunctive operation on the desalting plant design and operation

The optional intermediate printout that is available in the Operating Rule Program is of considerable help in assessing the unique operating features of the desalting plant and in seeing how these features might affect the design of the desalting plant. Figs. 16, 17, 18, and 19 show typical pages of simulation printout from each of the three applications. The reader should examine the column entitled "Months ON" for each application. All the plants operate intermittently, but the New York City plant is the most intermittent of the three since it operates some months in every year (frequently started up twice in a year) but operates 11 or more months only 2 years in 30 or 4 years in 30 depending on the definition of firm yield. The Cachuma plant also is turned on almost every year (only 3 years in 30 show no operation at all on the average) but the plant runs longer (remains on 11 or more months in 9 of 30 years on the average) than the New York plant and often operates several years (as many as 5) without being shut down except for maintenance. The Salt Lake plant operates differently than the other two in that it remains completely idle an average of 12 years in 30. When the plant is finally turned on, it often runs the whole year (5 out of 30). The plant is very rarely started up twice in a year.

The three situations are quite different regarding the design and operation of the plant. At Salt Lake City the plant should probably be mothballed after each operation since there is a good chance it will not be turned on again for several years. Mothballing would cost more per event but would lead to a savings in plant upkeep and the useful life would be extended. The New York City plant, however, should be kept warm and in a semi-ready state since it will be used some every year and will probably be restarted soon after shutdown. The Cachuma plant need not be mothballed after a run since it will likely be started again soon, but the plant does need to be designed to run long periods of time with little maintenance, because the plant is frequently needed continuously for several years at a time. Possibly the pattern of turn-on and turn-off at Cachuma or Salt Lake is even such that at certain times of the year the plant should be mothballed while at other times maintained in a partly ready state. In any case, the optional intermediate printout of the program illustrated by Figs. 16, 17, 18, and 19 gives a great deal of information that assists in the plant design.

Examination of the computer program simulation printouts shows that the pattern of plant operation changes with the operating rule and with the plant size. The larger plants tend toward more intermittent operation. Similarly, rules with higher turn-on and turn-off level cause a more intermittent operation. Analysis of the simulation printout also gives information concerning the yearly energy needs of the desalting plant and the probable timing of the energy demands.

By analyzing the computer printouts it is possible to predict the probable pattern of desalting plant operation over an extended period of time which, in turn, would identify such things as the average plant factor, likely monthly plant operation, the usual shutdown periods and the frequency of occurrence of shutdowns throughout the period of study. Desalting plant production for each period can also be determined. This information, in turn, provides the plant designer information relative to such plant features as the need for use of low cost materials, the necessity of frequent startups and shutdowns, need for extensive mothballing or requirement for base load operation for long periods of time. Trade-off studies of

Figure 16. Simulation printout, Cachuma application, 75 MGD plant.[a]

RULE NO.= 3 PERIOD NO.= 3

YEAR	TIMES ON	TIMES OFF	MONTHS ON	DSPRO	DSSP	SPILL	SHORT.
1	0	0	0	.00	.00	.00	.00
2	1	0	3	6.90	.00	.00	.00
3	0	0	12	27.37	.00	.00	.00
4	1	1	11	25.12	.00	.00	.00
5	1	2	4	9.07	6.12	6.12	.00
6	1	0	3	6.90	.00	.00	.00
7	0	0	12	27.37	.00	.00	.00
8	1	2	5	11.40	23.81	23.81	.00
9	1	0	1	2.25	.00	.00	.00
10	1	1	11	25.05	.00	.00	.00
11	0	0	12	27.37	.00	.00	.00
12	1	1	11	25.12	.00	.00	.00
13	2	2	9	20.55	.00	.00	.00
14	0	1	4	9.22	27.28	272.71	.00
15	0	0	0	.00	.00	22.72	.00
16	1	0	1	2.25	.00	.00	.00
17	1	1	7	15.90	.00	.00	.00
18	1	1	8	18.37	.00	.00	.00
19	1	1	11	25.12	.00	.00	.00
20	1	1	11	25.12	.00	.00	.00
21	1	1	11	25.12	.00	.00	.18
22	1	1	11	25.12	.00	.00	3.87
23	1	1	11	25.12	.00	.00	3.06
24	0	1	6	13.65	13.79	13.79	.00
25	0	0	0	.00	8.08	54.82	.00
26	1	0	0	.00	.00	.00	.00
27	0	1	3	6.90	.00	.00	.00
28	2	1	5	11.47	.00	.00	.00
29	1	1	6	13.57	.00	.00	.00
30	1	1	8	18.22	.00	.00	.00

DEMAND= 80.00 EFFICIENCY= .82

INCREASE IN YIELD= 55.84 M.G.D. ANNUAL COST=1111628 4.4 $/YEAR COST OF FYINC=199074. $/YEAR/M.G.D.

[a]For other conditions of the computation see line 2, Table 7.

Figure 17. Simulation printout, Salt Lake-Deer Creek application, 65 MGD plant.[a]

RULE NO.= 1 PERIOD NO.= 4

YEAR	TIMES ON	TIMES OFF	MONTHS ON	DSPRO	DSSP	SPILL	SHORT.
1	1	0	5	9.94	.00	.00	.00
2	0	1	6	11.83	.00	.00	.00
3	1	1	4	7.93	.00	.00	.00
4	0	0	0	.00	3.47	3.47	.00
5	0	0	0	.00	.00	.00	.00
6	0	0	0	.00	20.74	30.98	.00
7	1	0	2	3.96	.00	2.01	.00
8	0	1	9	17.74	.00	.00	.00
9	1	0	6	11.89	.00	.00	.00
10	1	1	7	13.91	.00	.00	.00
11	0	1	7	13.78	.00	.00	.00
12	0	0	0	.00	.00	.00	.00
13	1	0	5	9.94	.00	.00	.00
14	1	1	11	21.77	.00	.00	.00
15	1	1	11	21.77	.00	.00	.00
16	1	1	11	21.77	.00	.00	.69
17	0	1	6	11.83	32.09	32.09	.00
18	0	0	0	.00	2.03	5.47	.00
19	0	0	0	.00	.00	5.51	.00
20	0	0	0	.00	.00	9.45	.00
21	0	0	0	.00	.00	12.75	.00
22	0	0	0	.00	.00	.73	.00
23	1	0	4	7.93	.00	.00	.00
24	1	1	11	21.71	.00	.00	.00
25	1	1	11	21.71	.00	.00	.00
26	0	1	7	13.78	.00	.00	.00
27	0	0	0	.00	.00	.00	.00
28	0	0	0	.00	9.79	9.79	.00
29	0	0	0	.00	.54	.54	.00
30	1	0	0	.00	.61	.61	.00

DEMAND= 220.00 EFFICIENCY= .72

INCREASE IN YIELD= 43.15 M.G.D. ANNUAL COST= 8025081.1 $/YEAR COST OF FYINC=185981. $/YEAR/M.G.D.

[a]For other conditions of the computation see line 2, Table 11.

Figure 18. Simulation printout, New York City application, 250 MGD plant.[a]

RULE NO.= 1 PERIOD NO.= 1

YEAR	TIMES ON	TIMES OFF	MONTHS ON	DSPRO	DSSP	SPILL	SHORT.
1	1	1	2	15.25	.00	466.05	.00
2	1	0	5	38.25	.00	.00	.00
3	1	2	10	76.00	.00	.00	.00
4	3	2	3	22.25	125.69	125.69	.00
5	1	1	7	53.00	.00	.00	.00
6	1	2	4	30.25	101.56	135.54	.00
7	1	1	3	22.75	7.75	206.35	.00
8	1	0	4	30.50	22.75	179.70	.00
9	1	1	10	76.00	.00	.00	.00
10	1	2	10	75.75	.00	.00	.00
11	1	1	3	22.75	182.25	254.47	.00
12	1	0	4	30.50	22.75	150.73	.00
13	2	2	8	60.75	.00	.00	.00
14	1	1	10	76.00	.00	.00	.00
15	2	2	6	45.25	.00	.00	.00
16	1	1	7	53.00	49.39	49.39	.00
17	0	1	1	7.75	7.72	7.72	.00
18	1	0	5	38.25	.00	.00	.00
19	1	1	11	83.75	.00	.00	.00
20	1	2	11	83.75	.00	.00	.00
21	1	0	4	30.50	146.44	282.25	.00
22	1	1	9	68.50	.00	.00	.00
23	0	1	3	22.50	121.50	132.96	.00
24	1	1	1	7.50	.00	304.15	.00
25	1	0	5	38.25	7.50	315.18	.00
26	1	2	3	23.00	46.00	90.08	.00
27	1	0	4	30.50	15.25	44.89	.00
28	1	2	4	30.75	32.98	32.98	.00
29	1	0	5	38.25	.00	.00	.00
30	2	2	10	76.25	.00	.00	.00

DEMAND= 1970.00 EFFICIENCY= .32

INCREASE IN YIELD= 210.44 M.G.D. ANNUAL COST=3130 2091.2 $/YEAR COST OF FYINC=148746. $/YEAR/M.G.D.

[a]For other conditions of the computation see line 3, Table 15.

Figure 19. Simulation printout, New York City application, 150 MGD plant.[a]

RULE NO.= 2   PERIOD NO.= 1

YEAR	TIMES ON	TIMES OFF	MONTHS ON	DSPRO	DSSP	SPILL	SHORT.
1	1	1	3	13.50	13.50	264.03	.00
2	1	0	3	13.80	.00	.00	.00
3	1	1	11	50.25	.00	.00	.00
4	0	1	3	13.50	68.83	68.83	.00
5	2	1	5	22.95	.00	.00	.00
6	0	1	4	18.00	49.67	86.30	.00
7	0	0	0	.00	.00	198.26	.00
8	1	0	3	13.80	.00	157.15	.00
9	1	1	7	31.80	.00	.00	.00
10	0	1	10	45.60	.00	.00	.00
11	1	0	2	9.15	91.20	167.45	.00
12	1	1	4	18.45	13.80	141.80	.00
13	1	1	7	31.80	.00	.00	.00
14	1	1	11	50.25	.00	.00	.00
15	1	1	8	36.30	.00	.00	.00
16	1	1	6	27.30	.00	.00	.00
17	0	1	4	18.00	.00	.00	.00
18	1	0	4	18.30	.00	.00	.00
19	1	1	11	50.25	.00	.00	43.72
20	1	1	11	50.25	.00	.00	.00
21	1	1	3	13.80	78.64	216.93	.00
22	1	1	9	40.95	.00	.00	.00
23	0	1	3	13.50	63.60	75.71	.00
24	0	0	0	.00	.00	303.84	.00
25	1	0	3	13.80	.00	307.49	.00
26	0	1	3	13.50	27.30	71.53	.00
27	1	0	3	13.80	.00	29.54	.00
28	0	1	3	13.50	21.88	21.88	.00
29	1	0	4	18.30	.00	.00	.00
30	1	1	11	50.25	.00	.00	.00

DEMAND= 1970.00   EFFICIENCY= .41

INCREASE IN YIELD= 113.79 M.G.D.   ANNUAL COST=1898271.2 $/YEAR   UNIT COST OF FYINC= .4570 $/K GAL.

[a]For other conditions of the computation see line 10, Table 15.

these features could be made to determine the best plant design to fit the desalting application under consideration.

In addition to probable design features that would be encountered, the computer printouts would also provide an insight into the specific operating features likely to be encountered in conjunctive operation. For example, frequent startup and shutdown would indicate the desirability of operating the plant in conjunction with a steam power plant which would have an operating crew that could be used to operate the desalting plant when required. The computer program would be useful also in analyzing the problem of coordinating the power and water demand cycles of conjunctively operated power and desalting plants.

It should be noted that on the next to the last lines of Figs. 16, 17, 18, and 19 the "efficiency" of the desalting plant is listed. Efficiency was defined earlier as the ratio of the desalted water production that is utilized or consumed by the system to the total desalted water production. The water that is not consumed either goes over the spillway or is evaporated. Desalted water may be retained for years as holdover storage in the reservoir only to be lost the next time the reservoir fills and spills. In computing the efficiency, the program thus takes the total desalted water production, less desalted water spills, divided by the desalted water production. Efficiency so defined is one way of measuring the effectiveness of an operating rule. A perfect rule would so operate the plant as to waste no water at all. Surprisingly, even rather "inefficient" rules can produce substantial safe yield when operating a plant conjunctively in a real system, since only the low flows must be augmented. Thus, careful examination of the efficiency, along with other parameters tabulated by the program, can give much insight into the operation of the system.

Use of the program with different types of desalting plants

The Operating Rule Program as presently constituted can easily be used to analyze the operations of desalting plants of other than the MSF distillation type. Since all the economic data is supplied by the user of the program in the form of tables such as shown in Figs. 8, 12, and 15, once the cost data for any type plant is expressed in such tabular form, the program can find the least cost operating rule and the associated cost. Actually, the program can even be used to compute the costs associated with producing water from other kinds of conventional sources provided the economic data can be expressed in the form required. For example, the rule and cost for meeting the increased firm yield with water pumped from wells could be determined by the program if the operating costs and fixed charges for well production could be input into the computer. This procedure would constitute a "fair" way of assessing alternatives involving conventional supplies.

SUGGESTIONS FOR FURTHER STUDY

The Operating Rule Program has been developed and tested and is ready for use as a tool in planning for the conjunctive operation of desalting plants. So full use may be made of the program, some suggestions of areas for further study and improvement and application of the program are made below.

Operating Rule Program Applications

The Operating Rule Program should be applied as needed (by the Office of Saline Water) as an aid in assessing desalting alternatives. Each application study would have to include acquisition and preparation of basic input data, determination of the optimum plant size and operating rule for the system, costs of producing water, and parametric and sensitivity studies of the system to describe the operating characteristics and configuration of the best desalting system.

Modification of the Program to Apply to "No Storage" Systems

The current version of the Operating Rule Program was prepared to apply only to systems that include reservoir storage capacity. Minor alterations are needed to use the program for systems with no storage. In such a case the operating rule is already known because whenever the natural supply is less than demand the desalting plant must be turned on. For this case the computer simulation method furnishes a "fair" or "standard" way of comparing the costs of meeting the demand. The cost subroutine already built into the Operating Rule Program is the basis for this "standard" comparison. The program, when modified to handle the above case, would simulate operation of such a no-storage system under the specified demand and would compute the cost of producing the added firm yield.

Stage Construction

One promising phase of future study is the investigation of the economic advantage associated with incremental construction of desalting plants. A plant designed and installed with the capacity to meet future demands will be economically inefficient in the early years of operation. A plant built in stages, in accordance with projected growth in demand, would defer some capital investment until it is needed. Under many conditions the staging of construction would be a more efficient scheme than an initial full size plant. The advantages of staging the construction when operating in a stationary (no recession, no inflation) economy should be investigated first. The case of a changing economy (inflation and/or growth) should also be considered.

Cost of Drought Insurance

In the present use of the Operating Rule Program a firm yield is defined with an associated probability of meeting a given demand level. Changing the frequency of meeting a given demand can be thought of as changing the degree of protection against shortage or drought. Since a change in the frequency of meeting a given demand can change the firm yield, the operating rule and even the plant size, it will also change the costs. Deriving the costs of drought insurance then would involve running the Operating Rule Program at various frequencies of meeting the given demand level to find the associated costs. Then incremental costs of firm yield due to changes in the frequency of meeting a given demand could be determined. These incremental costs could then be viewed as the costs of drought insurance.

The incremental costs, as determined above, would need to be derived for several demand rates in order to indicate the cost of drought insurance as a function of the demand rate. The final results could be presented functionally or in tabular form.

Multiple Reservoir Systems

A continuing, more detailed study could be made of the multiple reservoir problem. The necessary modifications could be made to the present program to adapt it to handle this task. Very likely with multiple reservoirs, safe yield, in addition to that for a single reservoir, might be gained with a desalting plant by allowing some shifting of storage among the reservoirs in the system.

Power Generation Facilities

A study could be made of a desalting plant operating in conjunction with a reservoir that had with it some power generation facilities. The addition of the power generation option to the Operating Rule Program would be the main task.

Generalization of Results Obtained from a Number of Applications of the Operating Rule Program

After analyzing the results of several applications of the Operating Rule Program, a logical further step is to formulate general guidelines in the form of multi-coaxial graphs, nomograms, etc., which give preliminary estimates of the feasibility and economics of conjunctive operation of desalting plants. These guidelines could be used to ascertain whether a detailed analysis using the Operating Rule Program is needed in an application.

These guidelines could be developed by relating the costs per unit of added firm water yield to such factors as: (1) fuel costs, (2) start-up and shut-down costs, (3) labor costs, (4) reservoir capacity, (5) demand patterns, and (6) the parameters which characterize the natural hydrology; i.e., the variability and reliability of natural streamflow. The latter parameters would consist of means and variances within and between months, magnitudes, and variability of base flows resulting from groundwater, climatic factors, such as means and variances of monthly and annual precipitation, means and variance of temperatures, humidity, and the nature of the general precipitation producing storm of the region. These factors, as well as others which might improve the relationship, would be fitted by multivariate methods. Those factors which contribute nothing or little to the significance of the correlation could be deleted. Several methods for incorporating the data for each variable into the multivariate analysis should be examined, and that which gives the highest correlation should be used. As a final step, the results should be presented in an easily used graphical format.

Training Programs

To assure the most widespread use of the Operating Rule Program by water resources planners, hydrologists and systems engineers, a training seminar should be given to selected personnel (from OSW and other federal agencies and private firms) in the use and makeup of the program.

Application of Mathematical Programming to Conjunctive Operation of Desalting Plants

The use of computer simulation is one way to find the optimum operating rule. Another approach using mathematical programming might be preferable since a mathematically correct optimum would be determined. In applying either linear or dynamic programming to this optimization problem, the stream-reservoir-desalting system would be described mathematically with equations. The model would then be formally optimized on the computer to find the best rule for desalting plant operation. Sensitivity of the optimum solution to changes in various inputs could also be investigated. While linear and dynamic programming do furnish a means to systematically search for the optimum solution, the application would be new and might be difficult.

Improving the Operating Rule with Forecast Information

In areas where streamflow forecast information is available based on snow surveys there is an opportunity to increase the efficiency of the operating rule. The computer program would be modified so as to accept the forecast data, and then equally likely sequences of forecast information would be generated that would have the proper correlation with the generated streamflows. During the simulation of desalting plant operation, the program would then modify the operating rule so as to anticipate and compensate for low or high streamflow events. In this way the wasting of desalted water over the spillway would be reduced and the efficiency of the operating rule increased

Improvement in the Firm Yield Definition

In defining the firm yield of a system the magnitude and duration of shortages should affect the firm yield as well as the frequency of shortage. Program modifications should be developed and studies undertaken to establish the best and most realistic definition of firm yield.

Gradient Methods for Plant and Reservoir Size

Further work should be done in making the Operating Rule Program more completely automatic in its application. It may be possible to introduce plant size and reservoir size as variables and then use a gradient (steepest ascent) method to find the optimum conditions with respect to several variables simultaneously.

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APPENDIX A

DETAILED DESCRIPTION OF THE OPERATING RULE PROGRAM AND ITS APPLICATION

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DETAILED DESCRIPTION OF THE OPERATING RULE PROGRAM AND ITS APPLICATION

Input Data Required by the Program

The following categories serve to identify the input requirements of the program. Every variable name that appears in the input list is defined and, if applicable, the options are explained. The field position and width is given for each variable. For those variable names that are arrays, the format specification used for reading the input is also given. All integer variables must be right hand justified in their respective fields. This information can serve as a guide for the preparation of input data.

A. *Run identification card.* The first card identifies the particular job and contains the holerith information desired by the program user, punched in columns 1 to 80.

B. *Specification card.* This card contains the parameters that control the operation of the program.

Variable Name	Card Cols.	Definition
NPER	1-5	number of periods in the cost simulation
NYP	6-10	number of years in a period of NPER
NPFY	11-15	number of periods used in the firm yield determination
NYFY	16-20	number of years in a period of NPFY
NPRC	21-25	number of entries in the elevation-capacity-surface area table
CMAX	26-35	contents of the reservoir at the maximum usable elevation (BG)
CMIN	36-45	contents of the reservoir at the minimum usable elevation (BG)
DSCAP	46-55	capacity of the desalting plant (MGD)
FORCE	56-57	forced operation parameter; it specifies the minimum months of continuous operation once the plant is turned on
KIO	59	intermediate output option in YIELD 1 = the intermediate firm yield results are printed out 2 = suppress the printout
KPC	61	option for plotting reservoir contents in program OPRUL 1 = the monthly reservoir contents are plotted for each period 2 = no plot
KIP	63	printout option in GNFLO 1 = printout statistics of historic data and the generated streamflows for each periods 2 = no printout
KREAD	65	firm yield determination option 1 = input firm yield values from punched card 2 = enter subprogram YIELD to determine values of firm yield
IFLOW	67	input option for the historic streamflow data 1 = monthly values input in cubic feet per second (cfs) 2 = monthly values input in million gallons per day (MGD) 3 = monthly values input in acre-feet (A.F.) 4 = monthly values input in billions of gallons (BG)
ISTOR	69	input option for the elevation-capacity curve 1 = storage contents in hundreds of acre-feet (A.F. x 10^{-2}) 2 = storage contents in billions of gallons (BG)
IYEAR	71	option for specifying the year 1 = water year (October to September) 2 = calendar year (January to December)
KIK	73	intermediate printout option in OPRUL 1 = printout results of simulation for each period and each rule 2 = no intermediate printout

C. Mean inflow and monthly demand coefficients.

DEMB — mean inflow rate of the historic streamflow in million gallons per day (columns 1-10)

DM — the array (12 values) of monthly demand coefficients (12F5.0)

D. *Projected target demand rate.*

NDP — number of projected demand rates used in the analysis (columns 1-2 right justified) $1 \leq NDP \leq 6$

TRDEM — array of demand rates in MGD (6F10.0 starting in column 11)

E. *Elevation-capacity table.*

RL — is the array of elevations in ascending order

CAP — capacity of the reservoir at the corresponding elevation

The entries are paired on the input cards with up to 5 pairs per card (10F8.0) RL(1), CAP(1), RL(2), CAP(2), . . . , RL(NPRC), CAP(NPRC) NPRC pairs must be entered in this manner.

F. *Turn-on fractions.*

NON — number of turn-on fractions (columns 1-5, right justified)

ONLEV — array of turn-on fractions that are combined with the turn-off fractions to formulate the operating rules (10F5.0)

G. *Turn-off fractions.*

NOF — number of turn-off fractions (columns 1-5 right justified)

OFLEV — array of turn-off fractions used to formulate the operating rules (10F5.0)

H. *Firm yield parameters.*

START — estimate of the level of development of the system $0.0 \leq START \leq 1.0$ (columns 1-10)

STEP — increment by which START is initially adjusted in the iterative procedure to obtain the firm yield values (columns 11-20)

PCF — frequency required for meeting the target demand rate; i.e., the definition of the firm yield expressed as a fraction (columns 21-30)

I. *Mandatory releases.*

RBAR — average release rate in MGD (columns 1-10)

REL — array of monthly release coefficients (10F5.0 starting in column 11)

If mandatory releases do not enter into the analysis, this card is still required in the input deck; set RBAR and REL equal to zero

J. *Reservoir losses (evaporation).*

RLOSS — array of average monthly evaporation rates from the reservoir expressed in inches per month (12F5.0)

K. *Surface area table.*

SA — table of surface areas which correspond to each entry in the reservoir elevation table, expressed in acres (8F10.0)

L. *Monthly season assignment.*

NSN — seasonal configuration of the mean monthly inflows to the system
1 = level case
2 = low and high flows
3 = low, average, and high flows

MSN — array of monthly assignments as determined by the flow configuration

If NSN = 1 all 12 months are designated as 1. If NSN = 2, then the low months are designated as 1 and the high months as 2. If NSN = 3, then the low months are designated as 1, the average months as 2, and the high months as 3 (13I5, right justified).

M. *Increments for modifying the rule.*

(a) ONI2 — the increment subtracted from turn-on fraction for the high flow months (columns 1-8)

OFI2 — the increment subtracted from turn-off fractions for the high flow months (columns 9-16)

(b) ONI2 — the increment subtracted from the turn-on fractions for the average flow months (columns 1-8)

OFI2 — the increment subtracted from the turn-off fractions for the average flow months (columns 9-16)

ONI3 — the increment subtracted from the turn-on fractions for the high flow months (columns 17-24)

OFI3 the increment subtracted from the turn-off fractions for the high flow months (columns 25-32)

M(a) is required if NSN is specified as 2. M(b) is required if NSN is specified as 3. If NSN is specified as 1, then category M is omitted from the input.

N. *Optimized load factors.*

NOLF number of load factors in OFACT (I2, right justified)

OFACT array of load factors at which the plant is optimized (8F5.0, starting in column 6)

O. *Operational load factors.*

NOFF number of load factors in FACT (I2, right justified)

FACT array of load factors which have associated operational cost entries in the cost table (8F5.0, starting in column 6)

P. *Annual fixed charge.*

CAPC array of annual fixed charges, one entry for each optimized load factor, expressed in dollars per year (8F10.0)

Q. *Operation and maintenance costs.*

OPCST two-dimensional array of operation and maintenance costs for the plant optimized at the load factors in OFACT and operating at the factors in FACT. There are NOLF cards required with NOFF entries per card (8F10.0)

R. *Cost data.*

ETONC estimated plant turn-on cost in dollars (columns 1-8)

ETOFC estimated plant turn-off cost in dollars (columns 9-16)

INT discount interest rate expressed as a fraction (columns 17-24)

RATE fixed charge rate expressed as a percent (columns 25-32) (F8.0)

S. *Average values of firm yield.*

AVFY array of average firm yields values, contains NR values eight per card (8F10.0)

S is omitted from the data deck if the firm yield values are to be determined by entering YIELD; i.e., KREAD = 2.

T. *Average values of load factors.*

XLF array of average load factors associated with the rule that produces the firm yield as entered in AVFY. It contains NR values with XLF(1) = 0.0; i.e., operation without desalting and eight entries per card (8F10.0)

T is omitted from the data deck when S is omitted.

U. *Input data to the streamflow generator GNFLO.*

1. Identification card. Contains holerith information to identify the data being used. Must have an A in column 1.
2. Control parameters.

IYRA earliest year of record at any station

IMNTH calendar month number of first month of year

IMSNG indicator, positive value for estimating missing correlation coefficients

ITEST indicator, positive value calls for consistency test of correlation matrices

IRCON indicator, positive value calls for reconstitution of missing data

NSTA number of stations at which flows are to be generated

IPCHQ indicator, positive value calls for writing generated flows on tape

3. Streamflow data.

ISTAN station number (columns 1-6, right justified)

IYR year (columns 11-14)

QM array of monthly streamflows (12F5.0, starting in column 15)

4. Blank card. Repeat 3 for each year of streamflow record to be entered then follow the last (3) card with a blank card which terminates the input.

Other Important Variables Used in OPRUL and Subprogram YIELD

ALOSS accumulated losses from dead storage when in a drought (BG)

AVDUR average duration of droughts (months)

AVUC average unit cost array of the feasible rules ($/K gal.)

CMD array of monthly demands on the system (BG)

DBAR the mean inflow to the system as obtained from historical data (MGD)

DD variable demand rate used in iterating on firm yield values (MGD)

DELP change in the reservoir contents for month prior to the current month (BG)

DELS change in storage for the current month (BG)

DFLAG drought flag: 1 = no drought; 2 = currently in a drought

DSEFF ratio of desalted production actually used in satisfying the demand to the total desalted production

DSPRO total desalted water production for the period (BG)

DSSP desalted water produced in excess of requirements that eventually is spilled (BG)

DSV array of monthly production from desalting plant (BG)

FYINC the increase in the firm yield to be provided by the desalting plant (MGD)

KADD desalting plant operation flag
1 = desalting plant is off, reservoir contents greater than the turn-on contents
2 = desalting plant is on, reservoir contents less than the turn-on contents

KCON a continuous operation counter KCON = 11 signals time to shut down for maintenance

KSTRT flags the computation for obtaining the initial reservoir starting contents
1 = not in the computation
2 = store year end reservoir contents

KSTO array of monthly reservoir contents rounded to nearest integer (BG) used if the plot option is selected

NMON an array of the number of months the desalting plant operated each year

NOR the number of operating rules in the decision set

NR NOR + 1

NSIG signal normal or abnormal return from TERP

NTOF array containing the number of times the plant was turned off in each year

NTON array containing the number of times the plant was turned on in each year

OFCON turn-off fractions converted to storage contents (BG)

ONCON turn-on fractions converted to storage contents (BG)

PI a performance index, percentage of target demand satisfied on a volume basis

PPCF the firm yield definition expressed as a percent, PCF x 100

Q array of monthly streamflows obtained from GNFLO (BG)

RCON array of year end (start of year) reservoir contents (BG)

RLEV reservoir elevation (ft)

RS array of initial reservoir contents for each period (BG)

RSTOR the current value of reservoir contents (BG)

RSP the value of RSTOR for the month prior to the current month (BG)

SDSP a running summation of desalted water production that may end up as spill (BG)

SSHT array of yearly shortages (BG)

SSPL array of yearly spills (BG)

UCAP available storage (BG)

List and Purpose of the Subprograms Called for in OPRUL

The main program OPRUL utilizes 12 external subprograms during the course of the simulation. A brief description of the function of each program is given below.

RAN — a function subprogram which generates random numbers with a uniform distribution between 0.0 and 1.0. The subprogram is valid for computers that use 32 bits to represent integer numbers. If OPRUL is to be used on a computer with a different bit configuration, RAN must be modified or a different subprogram used to provide the uniform random numbers.

FIND — locates and identifies the minimum cost rule from among the set of feasible operating rules

QCON — converts each monthly value of a generated streamflow sequence from a rate to a volume in billion gallons. If flows are generated in the units of billions of gallons, then QCON is not entered.

TERP — entered to perform a linear interpolation in the elevation-capacity-surface area tables. The tables must be arranged with the elevation and corresponding capacity and water surface are in ascending order. The increments should be small enough to adequately describe the curves.

CON — for a given month and a given flow rate CON computes a volume in billions of gallons. It is used to convert the demand rates and desalting plant rate to volumes on a monthly basis.

GNFLO — generates the streamflow sequences used throughout the simulation in OPRUL and YIELD. The program, as mentioned previously, was obtained from the Hydrologic Engineering Center, U.S. Army Corps of Engineers, Sacramento, California. In the event that a better streamflow generation model is developed, it can readily be substituted for GNFLO.

CROUT — used in GNFLO to solve equations simultaneously for the regression coefficients. This subprogram was obtained with GNFLO from the HEC, U.S. Army Corps of Engineers.

PLOT — produces a plot, on the printer, of monthly reservoir contents when the plot option (KPC = 1) is specified. The ordinate is reservoir contents expressed as a percent of the total capacity and the abscissa is month and year. Ten years are plotted on a page. The plot option is not available in subroutine yield. A very general logic flow is depicted on page 56.

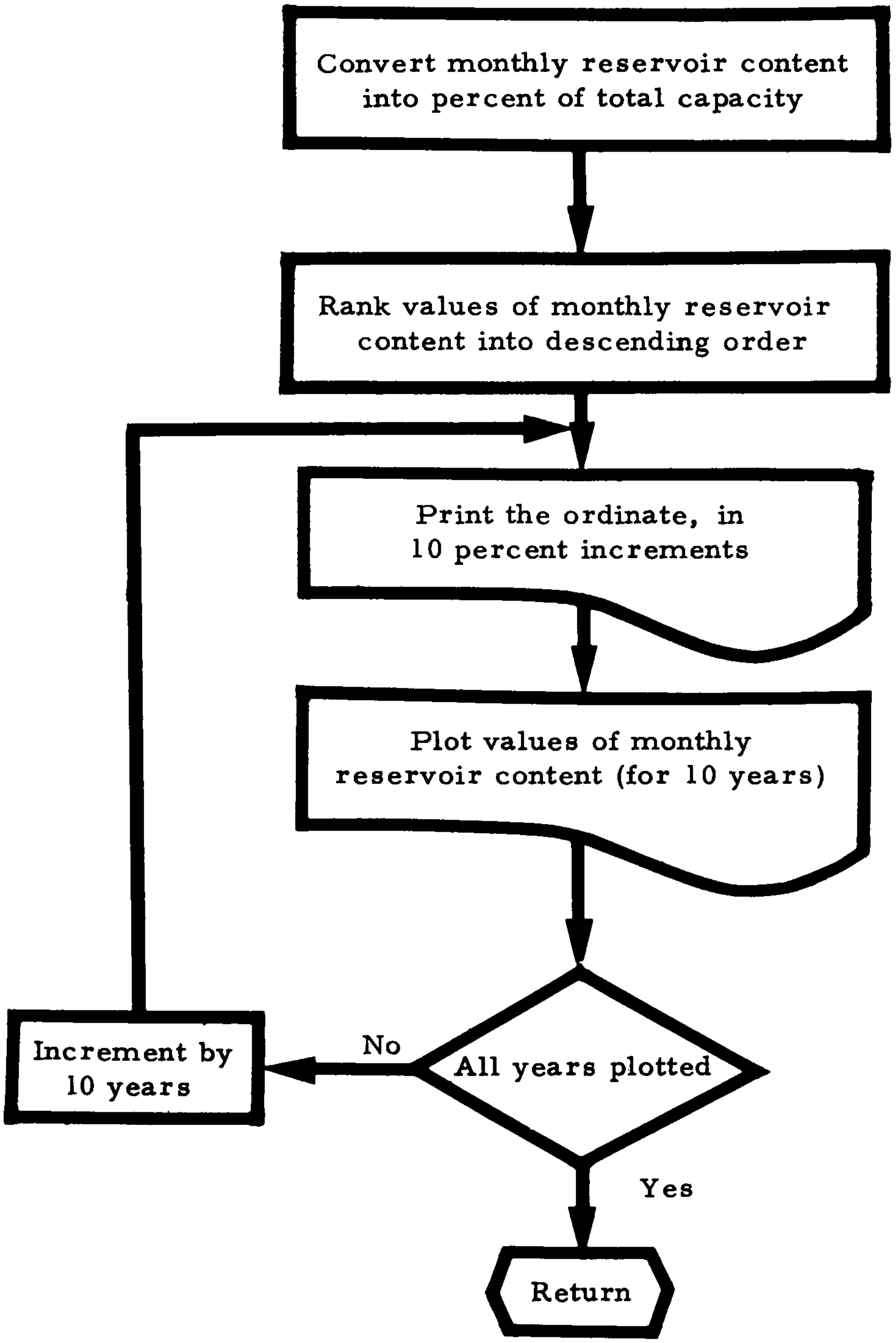
RULE — formulates the set of operating rules to be used in the firm yield analysis. The general logic involved is shown by means of the flow diagram on page 57.

COST — determines the total annual cost for a given feasible rule and period of simulation. The subprogram is not limited to any one type of desalting process or even to any one source of supplemental water. The only requirement is that the costs can be presented in the format as described in the input requirements. A general flow diagram for COST is shown on page 58.

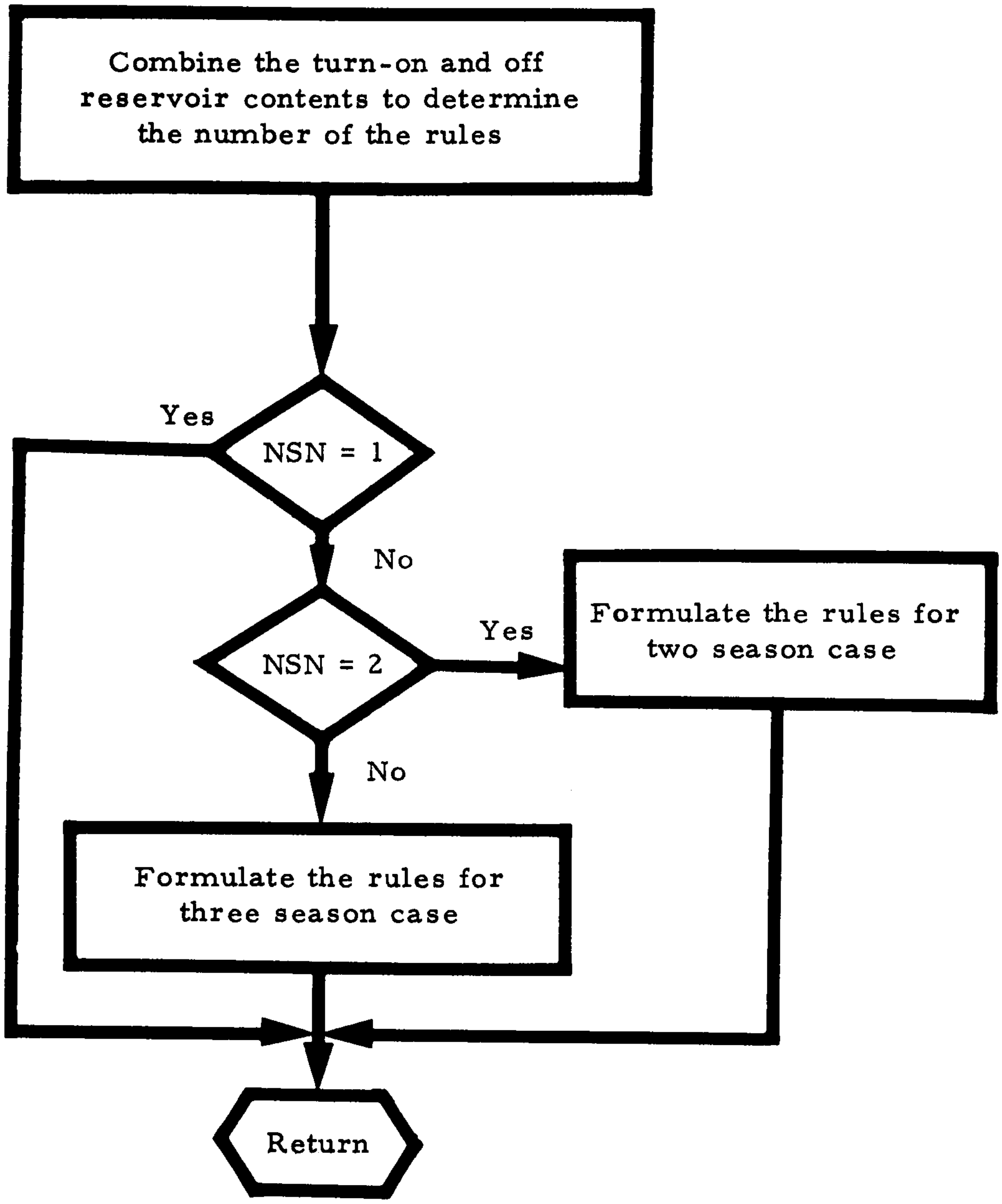
TERP3 — interpolates in the three-dimensional array of average firm yield values to determine the set of feasible operating rules. The argument is the projected target demand rate (TRDEM). Each turn-off fraction, in turn, is held constant and the interpolation performed to obtain a turn-on fraction. The number of interpolations attempted is always the same as the number of turn-off fractions specified by NOF. The general logic flow diagram of TERP3 is shown on page 59.

YIELD — simulates system operation, using a given streamflow sequence, to find the yield of the system that satisfies the firm yield definition. A calculated guess is made for the demand rate that the system can satisfy the required number of years. Simulation is repeated by adjusting the demand rate until the firm yield definition is met exactly or is bracketed. If the firm yield value is bracketed, a linear interpolation is performed to obtain the desired firm yield value. A firm yield of the system without desalting is determined along with the firm yield of each operating rule in the decision space. A very general flow diagram is shown on page 60.

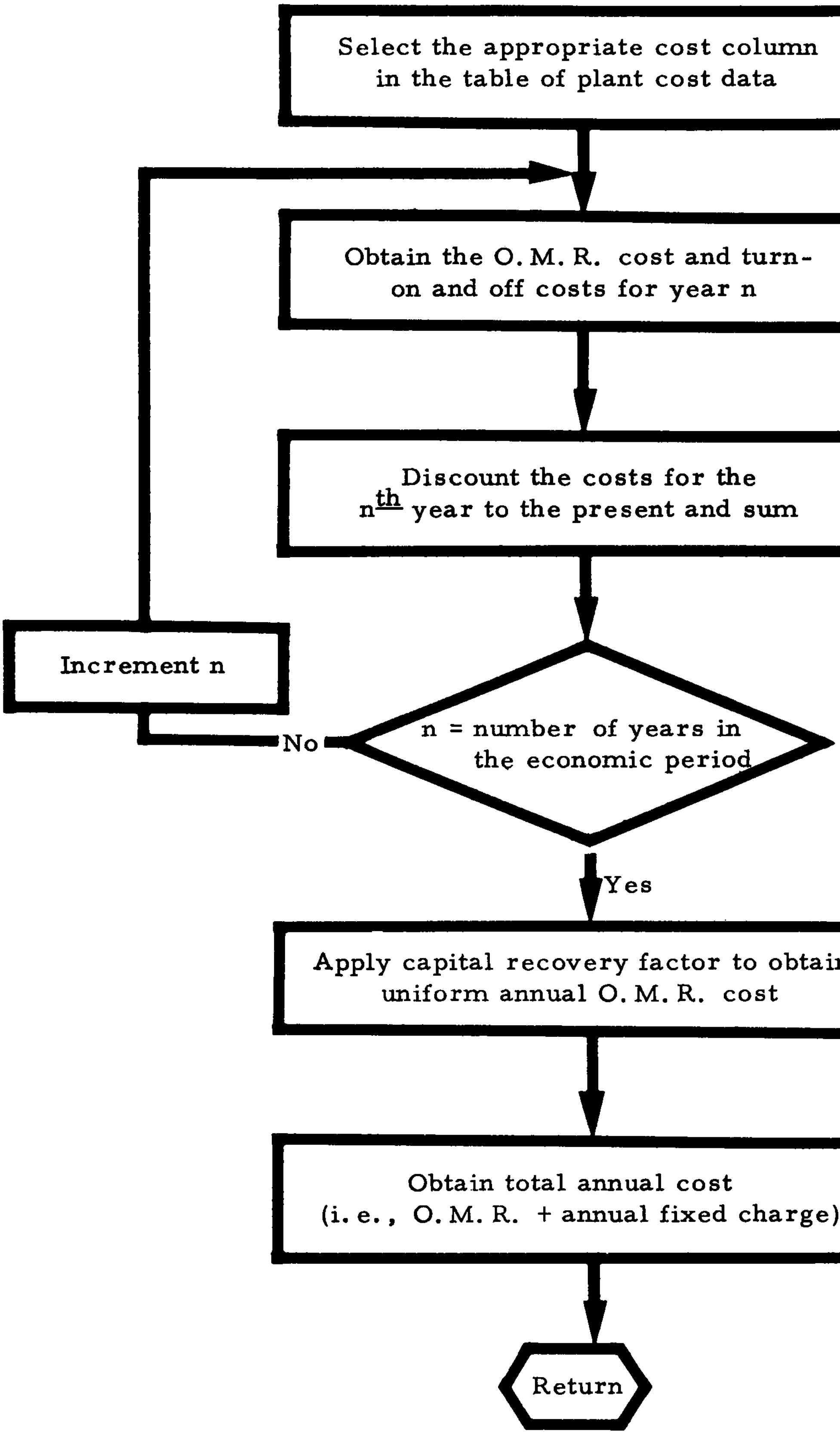
SUBPROGRAM PLOT FLOW DIAGRAM



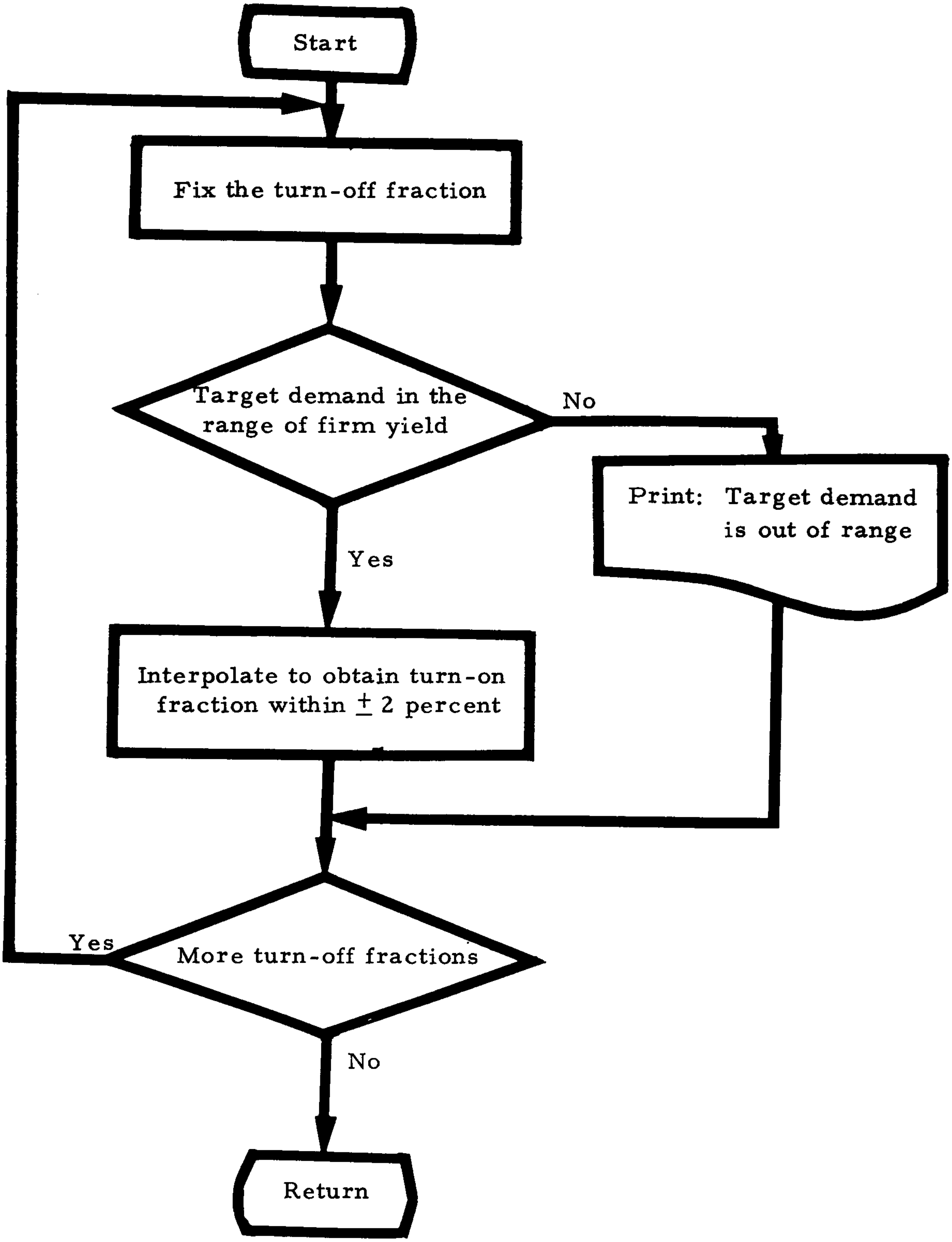
SUBPROGRAM RULE FLOW DIAGRAM



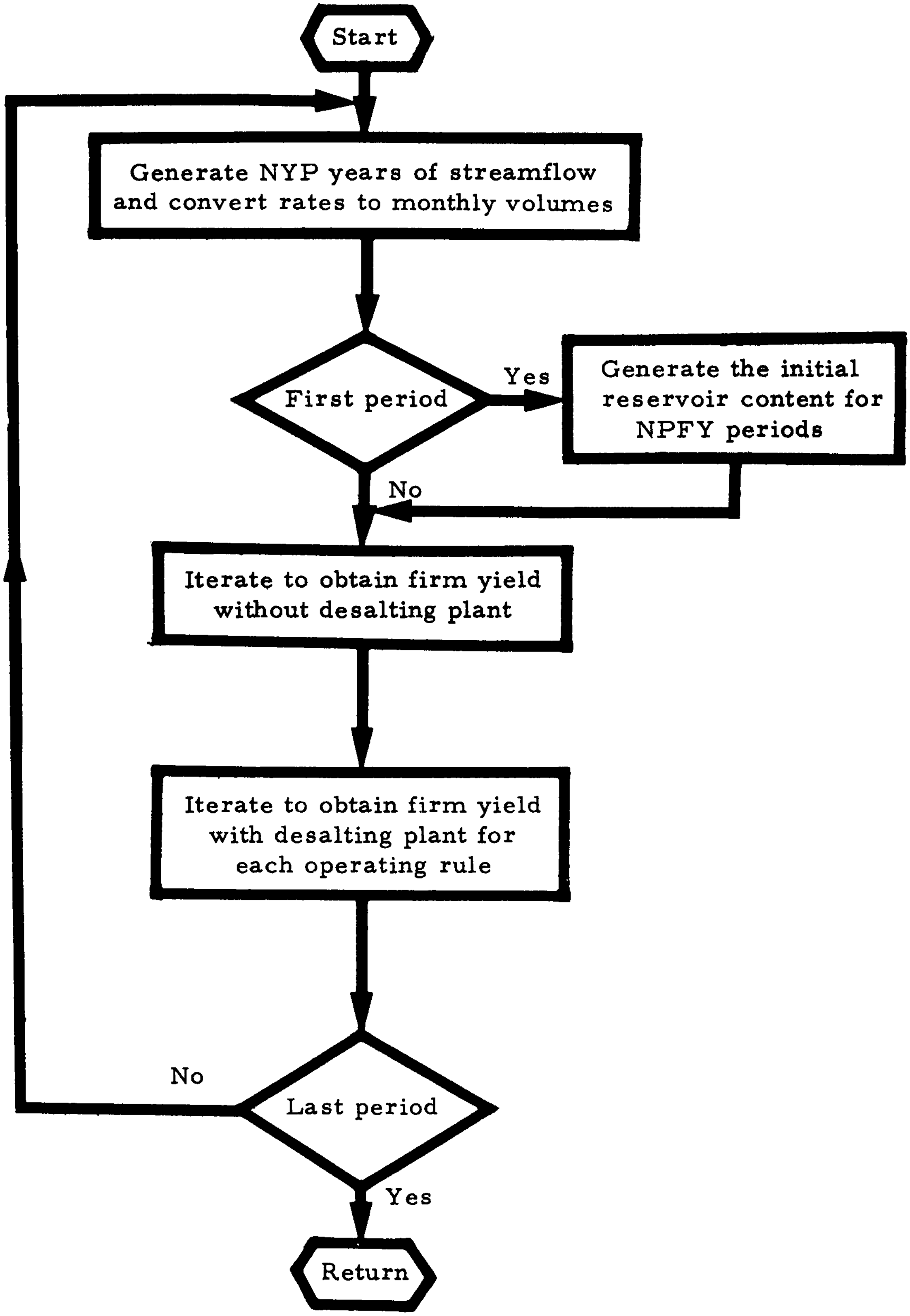
SUBPROGRAM COST FLOW DIAGRAM



SUBPROGRAM TERP3 FLOW DIAGRAM



SUBPROGRAM YIELD FLOW DIAGRAM



```
A        SAMPLE OUTPUT RUN WITH A 175 M.G.D. DESALTING PLANT

B     5   30    5   75   24 623.574   20.0       175.0      1 1 2 2 1 4 2 2 1

C  2350.      .92  .90  .92  .95  1.00 1.06 1.08 1.10 1.10 1.05 1.00 .92

D  1        2050.

  [440.     0.0      460.     3.000    480.     12.000   500.     20.000   505.     21.503
  |510.     26.306   515.     35.596   520.     49.221   525.     65.513   530.     85.268
E{ 535.     108.739  540.     134.648  545.     162.530  550.     192.587  555.     225.165
  |560.     260.218  565.     297.571  570.     336.924  575.     379.050  580.     424.147
  [585.     471.357  590.     520.326  595.     571.158  600.     623.574

F     4.7   .5   .4   .3

G     3.95  .85  .7

H  .90       .05       .90

I  150.0     .3   .3   .3   .5   .6   1.0  1.5  2.5  2.5  1.8  .4   .3

J     1    2    2    3    4    5    5    4    3    2    1    1

  [0.00     150.     600.     1011.    2849.    5048.    8365.    10407.   11723.   14601.
K{ 16304.   17544.   18708.   20241.   21773.   23306.   24570.   25751.   28009.   29384.
  [30589.   31660.   32619.   33731.

L     3    2    2    3    3    2    1    1    1    1    1    2    2

M  .05       .05       .10       .10

N  6    10.  20.  30.  50.  70.  90.
O  8    0.   10.  20.  30.  50.  70.  90.  100.
P  9400000.  10100000. 10610000. 11580000. 12300000. 17940000.
  [1000000.  12660000. 15750000. 18650000. 24600000. 30870000. 36600000. 39400000.
  |1000000.  13900000. 15550000. 18200000. 23600000. 29960000. 33900000. 36300000.
Q{ 1000000.  13200000. 15600000. 18200000. 23150000. 28000000. 32800000. 34600000.
  |1000000.  14100000. 16300000. 18550000. 27840000. 27400000. 31650000. 33700000.
  |1000000.  14600000. 16750000. 18800000. 23900000. 27300000. 31400000. 33400000.
  [1000000.  15200000. 17210000. 19200000. 23200000. 27400000. 30350000. 32500000.
R  140000.   140000.   0.05      7.23

S  1935.22   2083.63   2082.02   2077.29   2058.33   2056.87   2048.15   2045.57
   2046.54   2030.73   2017.0[illegible]   2016.01   2009.90
```

```
T  0.00      70.65     66.92     61.10     68.48     65.01     59.00     67.59
   64.12     57.16     66.18     62.98     56.12

U
1  A      NEW YORK  STREAM FLOW DATA
2      1929          1        0        1        0        1        0
  [480826      1929  57.  46. 229. 248. 130.  33.   9.  14.   7.  48.  59.  80.
  |480826      1930  94.  64. 142.  84.  38.  68.  10.   6.  12.   1.  11.  17.
  |480826      1931  17.  31.   4. 201. 138.  68.  88.  19.  17.   2.  11.  46.
  |480826      1932 121.  96.  64. 186.  67.  47.  14.  12.   0. 115. 165.  46.
  |480826      1933  59.  43. 135. 213.  58.  19.   6. 136. 184.  40.  42.  57.
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  |480826      1935 106.  44. 148. 106.  80.  27.  99.  14.  12.  19.  14.  59.
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  |480826      1941  68.  57.  59. 138.  38.  22.  22.  17.   1.   1.  25.  65.
  |480826      1942  57.  48. 180. 105.  91.  44.  19.  29.  54.  83.  99. 128.
  |480826      1943  80.  98. 170. 128. 182.  76.  11.  13.   0.  36. 102.  27.
  |480826      1944  25.  35. 125. 148.  68.  25.   9.  12.  27.  19.  38.  86.
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3{ 480826      1946 110.  58.  40.  38. 126.  97.  25.  20.  17.  24.  28.  30.
  |480826      1947  98.  50.  32. 180. 170.  72.  45.  21.  14.  13.  98.  40.
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  |480826      1951 117. 143. 161. 182.  56.  34.  52.  18.  14.  46.  48. 134.
  |480826      1952 130.  90. 140. 205. 105.  78.  53.  27.  25.  12.  55. 146.
  |480826      1953 129. 103. 202. 140. 118.  19.   7.   6.  14.   8.  38. 115.
  |480826      1954  55. 112. 110.  95. 133.  28.   7.   6.  25.  22. 137. 113.
  |480826      1955  54.  64. 164. 110.  40.  34.   7. 157.  19. 293. 160.  38.
  |480826      1956  45.  57. 132. 292.  96.  40.  25.   7.  23.  27.  54. 109.
  |480826      1957  69.  51.  80. 141.  81.  15.   7.   6.   1.   7.  32. 175.
  |480826      1958  80.  46. 174. 251. 223.  37.  20.   8.  16.  46.  97.  54.
  |480826      1959  84.  60.  92. 168.  40.  18.   6.   6.   6. 102. 142. 148.
  |480826      1960  94. 108.  87. 203.  84.  56.  34.  23. 123.  34.  43.  45.
  |480826      1961  23. 128. 153. 189. 115.  58.  16.  21.   9.   6.  20.  29.
  |480826      1962  89.  30. 122. 193.  51.  18.   6.   6.   1.  20.  61.  72.
  |480826      1963  26.  24. 174. 108.  40.  36.  18.  17.   6.   6.  58.  55.
  [480826      1964 119.  61. 191. 143.  47.  27.   1.   0.   0.   2.  10.  31.
4  BLANK CARD
```

SAMPLE OUTPUT RUN WITH A 175 M.G.D. DESALTING PLANT

```
NO.OF PERIODS IN SIMULATION=  5          NO. OF YEARS IN EACH PERIOD=  30
NO.OF PERIODS IN FIRM YIELD=  5          NO.OF YEARS IN EACH PERIOD=  75

NPRC= 24
CMAX=623.574 B.G.
CMIN= 20.000 B.G.
DSCAP=175.00 M.G.D.
FORCE= 1
KIO= 1
KPC= 2
KIP= 2
KREAD= 1
IFLOW= 4
ISTOR= 2
IYEAR= 2
KIK= 1

THERE ARE  1 DEMAND LEVELS IN THIS RUN AS FOLLOWS
      2050.0

DEMB=2350.000 M.G.D.
RBAR= 150.000 M.G.D.


THIS IS A 3 SEASON RUN
AVE. SEASON ON INC= .050          AVE. SEASON OFF INC= .050
WET SEASON ON INC.= .100          WET SEASON OFF INC.= .100
```

	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
MONTHLY SEASON ASSIGNMENT	2	2	3	3	2	1	1	1	1	1	2	2
DEMAND COEFFICIENTS	.92	.90	.92	.95	1.00	1.06	1.08	1.10	1.10	1.05	1.00	.92
RELEASE COEFFICIENTS	.30	.30	.30	.50	.60	1.00	1.50	2.50	2.50	1.80	.40	.30

```
TURN-ON FRACTIONS       .70  .50  .40  .30
TURN-OFF FRACTIONS      .95  .85  .70

START= .90
STEP= .05
PCF= .90
```

COST DATA FOR DESALTING PLANT USED IN ANALYSIS

OPER. L. F. (IN PERCENT)	ANNUAL COST IN $/YR. FOR THE PLANT THAT IS OPTIMIZED AT THE GIVEN LOAD FACTOR (IN PERCENT)					
	10.	20.	30.	50.	70.	90.
0.	1000000.	1000000.	1000000.	1000000.	1000000.	1000000.
10.	12660000.	13000000.	13200000.	14100000.	14600000.	15200000.
20.	15750000.	15550000.	15600000.	16300000.	16750000.	17210000.
30.	18650000.	18200000.	18200000.	18550000.	18800000.	19200000.
50.	24600000.	23600000.	23150000.	22840000.	23000000.	23200000.
70.	30870000.	29960000.	28000000.	27400000.	27300000.	27400000.
90.	36600000.	33900000.	32800000.	31650000.	31400000.	30350000.
100.	39400000.	36300000.	34600000.	33700000.	33400000.	32500000.
ANNUAL FIXED CHG. AT 7.23 PERCENT	9400000.	10100000.	10610000.	11580000.	12300000.	12940000.

ESTIMATED TURN-ON COST= 140000.
ESTIMATED TURN-OFF COST= 140000.
INTEREST RATE= .0500

AVERAGE FIRM YIELD
1935.22 2083.63 2082.02 2077.29 2058.33 2056.87 2048.15 2045.57 2046.54 2038.73 2017.03 2016.01
2009.90

AVERAGE LOAD FACTORS
.00 70.65 66.92 61.10 68.48 65.01 59.00 67.59 64.12 57.16 66.18 62.98
56.12

INTERPOLATED TURN-ON FRACTIONS
.435 .433 .513

INTERPOLATED AVERAGE LOAD FACTORS
67.90 64.42 59.13

OPERATION WITHOUT THE DESALTING PLANT

PERCENT DEMAND	DEMAND M.G.D.	NO. OF SHORTAGES	SHORTAGES B.G.	FREQUENCY OF TARGET	PERFORMANCE INDEX	SHORTAGE DURATION	PLANT TURN ON	ALOAD
.85	1997.50	16	1043.22	78.67	98.09	2.06	0	.00
.80	1880.00	6	268.02	92.00	99.48	2.17	0	.00

OPERATING RULE
SEASON 1. ON=442.50 B.G. OFF=593.40 B.G.
SEASON 2. ON=412.32 B.G. OFF=563.22 B.G.
SEASON 3. ON=382.14 B.G. OFF=533.04 B.G.

PERCENT DEMAND	DEMAND M.G.D.	NO. OF SHORTAGES	SHORTAGES B.G.	FREQUENCY OF TARGET	PERFORMANCE INDEX	SHORTAGE DURATION	PLANT TURN ON	ALOAD
.95	2398.75	41	5132.73	45.33	92.18	2.95	72	83.56
.85	2146.25	15	1066.17	80.00	98.19	2.07	68	74.44
.80	2020.00	5	227.11	93.33	99.59	1.80	64	67.36

OPERATING RULE
SEASON 1. ON=442.50 B.G. OFF=533.04 B.G.
SEASON 2. ON=412.32 B.G. OFF=502.86 B.G.
SEASON 3. ON=382.14 B.G. OFF=472.68 B.G.

PERCENT DEMAND	DEMAND M.G.D.	NO. OF SHORTAGES	SHORTAGES B.G.	FREQUENCY OF TARGET	PERFORMANCE INDEX	SHORTAGE DURATION	PLANT TURN ON	ALOAD
.95	2398.75	41	5152.68	45.33	92.15	2.95	73	82.33
.85	2146.25	16	1090.19	78.67	98.14	2.00	68	72.07
.80	2020.00	5	227.13	93.33	99.59	1.80	66	65.05

OPERATING RULE
SEASON 1. ON=442.50 B.G. OFF=442.50 B.G.
SEASON 2. ON=412.32 B.G. OFF=412.32 B.G.
SEASON 3. ON=382.14 B.G. OFF=382.14 B.G.

PERCENT DEMAND	DEMAND M.G.D.	NO. OF SHORTAGES	SHORTAGES B.G.	FREQUENCY OF TARGET	PERFORMANCE INDEX	SHORTAGE DURATION	PLANT TURN ON	ALOAD
.95	2398.75	41	5248.07	45.33	92.01	3.00	74	80.44
.85	2146.25	16	1114.79	78.67	98.10	2.00	74	67.24
.80	2020.00	5	227.09	93.33	99.59	1.80	71	59.05

OPERATING RULE
SEASON 1. ON=321.79 B.G. OFF=593.40 B.G.
SEASON 2. ON=291.61 B.G. OFF=563.22 B.G.
SEASON 3. ON=261.43 B.G. OFF=533.04 B.G.

PERCENT DEMAND	DEMAND M.G.D.	NO. OF SHORTAGES	SHORTAGES B.G.	FREQUENCY OF TARGET	PERFORMANCE INDEX	SHORTAGE DURATION	PLANT TURN ON	ALOAD
.90	2272.50	27	2755.10	64.00	95.57	2.84	63	81.64
.80	2020.00	8	307.71	89.33	99.44	1.67	44	68.24

OPERATING RULE
SEASON 1. ON=321.79 B.G. OFF=533.04 B.G.
SEASON 2. ON=291.61 B.G. OFF=502.86 B.G.

RULE NO.= 3 PERIOD NO.= 5

YEAR	TIMES ON	TIMES OFF	MONTHS ON	DSPRO	DSSP	SPILL	SHORT.
1	2	1	11	58.45	.00	.00	47.46
2	1	1	7	37.10	.00	.00	.00
3	1	1	7	37.10	.00	.00	.00
4	1	1	7	37.10	.00	.00	.00
5	1	1	11	58.62	.00	.00	.00
6	1	2	6	31.67	.00	.00	.00
7	1	0	3	16.10	.00	.00	.00
8	1	1	11	58.62	.00	.00	68.44
9	1	1	11	58.62	.00	.00	.00
10	0	1	4	21.00	.00	.00	.00
11	1	0	4	21.35	.00	.00	.00
12	1	1	11	58.62	.00	.00	.00
13	1	1	8	42.35	.00	.00	.00
14	0	1	3	15.75	.00	.00	.00
15	1	1	2	10.67	.00	.00	.00
16	1	0	2	10.67	131.30	131.30	.00
17	1	1	7	37.10	.00	.00	.00
18	1	1	6	31.67	.00	.00	.00
19	0	1	3	15.75	57.68	57.68	.00
20	0	0	0	.00	98.95	111.57	.00
21	0	0	0	.00	.00	.00	.00
22	1	0	4	21.35	.00	.00	.00
23	0	1	3	15.75	33.14	33.14	.00
24	1	0	2	10.67	.00	.00	.00
25	1	1	6	31.85	.00	.00	.00
26	1	1	8	42.35	.00	.00	.00
27	0	1	1	5.42	94.26	228.33	.00
28	1	0	2	10.67	.00	262.32	.00
29	1	1	5	26.77	.00	.00	.00
30	0	1	3	15.75	34.23	34.23	.00

DEMAND= 2050.00 EFFICIENCY= .46

INCREASE IN YIELD= 114.78 M.G.D. ANNUAL COST=3428545O.5 $/YEAR UNIT COST OF FYINC= .8184 $/K GAL.

AVERAGE COSTS FOR FEASIBLE OPERATING RULES
.7684 .7627 .7670

MINIMUM COST OF FYINC= .7627 $/K GAL.

INCREASE IN FIRM YEILD= 114.78 M.G.D.

TURN ON= .43 TURN OFF= .85

DATA CARDS IGNORED - FIRST IS LISTED BELOW

CAPACITY WHEN FULL= 624 B.G. CAPACITY AT MIN. USABLE LEVEL= 20 B.G.
ORDINATE(RESERVOIR CONTENT) IS IN PERCENT PAGE= 1

```
C     PROGRAM OPRUL       USU   APRIL 1968 TO JULY 1969
C     THIS PROGRAM SIMULATES OPERATION TO AID IN EVALUATING THE OPERATING
C     RULE
      COMMON /BLOCKA/Q(1201,5)
      COMMON /BLOCKB/ONCON(100),OFCON(100),UCAP
      COMMON /BLOCKC/CAP(100),RL(100),DM(12),RS(50),SA(100),RLOSS(12),
     1REL(12),MSN(12),DSV(12),SSHT(100),CMD(12),FY(20,50),AVLF(20,50),
     2CMAX,NPRC,DSCAP,FORCE,START,STEP,PCF,NSN,DEMB,CMIN,KIP,RBAR,
     3KREAD,ISTOR,IFLOW,IYEAR,NPER
      COMMON /BLOCKD/NTON(50),NTOF(50),NMON(50),FACT(10),CAPC(10),OPCST(
     110,10),OFACT(10),NOLF,NOFF,ETONC,ETOFC,INT,RATE
      COMMON /BLOCKE/ AVFY(50),XLF(50),ON(10),AL(10)
      COMMON /BLOCKF/ONI2,OFI2,ONI3,OFI3
      DIMENSION ONLEV(10),OFLEV(10),DSPRO(50),DSSP(50),SSPL(50),
     1KSTO(601),DSEFF(25), UCFY(25,20),MNTH(12),AVUC(50),TRDEM(10),
     2ONOPT(10),OFOPT(10),OFAC(10),FYINC(10),MNTHA(12)
      INTEGER FORCE ,DFLAG
      DATA MNTH/4HOCT ,4HNOV ,4HDEC ,4HJAN ,4HFEB ,4HMAR ,4HAPR ,4HMAY ,
     14HJUNE,4HJULY,4HAUG ,4HSEPT/
      DATA MNTHA/4HJAN ,4HFEB ,4HMAR ,4HAPR ,4HMAY ,4HJUNE,4HJULY,4HAUG
     1,4HSEPT,4HOCT ,4HNOV ,4HDEC /
      WRITE(6,5000)
 5000 FORMAT(1H0,40X,'***** OPERATING RULE PROGRAM *****'/
     11H0,45X,'OFFICE OF SALINE WATER'/
     21H0,38X,'UNITED STATES DEPARTMENT OF INTERIOR'///
     31H0,38X,'PROJECT NAME .'/
     41H ,43X,'OPTIMUM OPERATION OF DESALTING PLANTS AS'/
     51H ,43X,'A SUPPLEMENTAL SOURCE OF SAFE YIELD.'/
     61H0,38X,'CONTRACT NUMBER .  14-01-0001-1711'/
     71H0,43X,'A COMPUTER PROGRAM DEVELOPED BY'/
     81H ,43X,'UTAH WATER RESEARCH LABORATORY'/
     91H ,47X,'UTAH STATE UNIVERSITY'/
     $1H ,53X,'JULY 1969'/
     $1H0,38X,'PROJECT STAFF.'/
     $1H ,41X,'SAM SHIOZAWA          OSW REPRESENTATIVE'/
     $1H ,41X,'CALVIN G. CLYDE       PROJECT LEADER'/
     $1H ,41X,'DEAN F. PETERSON,JR.  ADVISOR'/
     $1H ,41X,'ROLAND W. JEPPSON     ASSOCIATE PROFESSOR'/
     $1H ,41X,'JAMES H. MILLIGAN     RESEARCH ENGINEER'/
     $1H ,41X,'WESLEY H. BLOOD       RESEARCH ENGINEER'/
     $1H ,62X,'AND PROGRAMMER'/1H1)
      READ(5,1000)
 1000 FORMAT(80H
     1
      WRITE(6,1000)
C     INPUT CONTROL PARAMETERS . . . . . . . . . . . . . . . .
      READ(5,1002) NPER,NYP,NPFY,NYFY,NPRC,CMAX,CMIN,DSCAP,FORCE,KIO,KPC
     1,KIP,KREAD,IFLOW,ISTOR,IYEAR,KIK
 1002 FORMAT(5I5,3F10.0,9I2)
      WRITE(6,2006)NPER,NYP,NPFY,NYFY,NPRC,CMAX,CMIN,DSCAP,FORCE,KIO,KPC
     1,KIP,KREAD,IFLOW,ISTOR,IYEAR,KIK
 2006 FORMAT(1H0,'NO.OF PERIODS IN SIMULATION='I3,10X,'NO. OF YEARS IN E
     1ACH PERIOD= 'I3,/1H ,'NO.OF PERIODS IN FIRM YIELD='I3,10X,'NO.OF Y
     2EARS IN EACH PERIOD= 'I3,/1H0,'NPRC='I3,/1H ,'CMAX='F7.3,' B.G.'/
     31H ,'CMIN='F7.3,' B.G.'/1H ,'DSCAP='F6.2,' M.G.D.'/1H ,'FORCE='I2,
     4/1H ,'KIO='I2,/1H ,'KPC='I2,/1H ,'KIP='I2,/1H ,'KREAD='I2,/1H ,'IF
     5LOW='I2,/1H ,'ISTOR='I2,/1H ,'IYEAR='I2,/1H ,'KIK='I2)
C       INPUT THE DEMAND DATA . . . . . . . . . . . . . . .
      READ(5,1001) DEMB,(DM(I),I=1,12)
 1001 FORMAT(F10.0,13F5.0)
      READ(5,1010) NDP,(TRDEM(J),J=1,NDP)
 1010 FORMAT(I2,8X,6F10.0)
      WRITE(6,1011) NDP,(TRDEM(J),J=1,NDP)
 1011 FORMAT(1H0,'THERE ARE'I3,' DEMAND LEVELS IN THIS RUN AS FOLLOWS'/
     11H ,8F12.1)
C     INPUT RESERVOIR DEPTH-CAPACITY DATA .. . . . . . . . . .
C     READ ALL RESEVOIR DATA IN FROM THE LOWEST TO THE HIGHEST VALUES.
      READ(5,1003) (RL(J),CAP(J),J=1,NPRC)
 1003 FORMAT(10F8.0)
      IF(ISTOR.EQ.2) GO TO 508
      DO 507 J=1,NPRC
  507 CAP(J)=CAP(J)*.000326
C      INPUT OPERATING RULE CRITERA . . . . . . . . . . . . .
  508 READ(5,1004) NON,(ONLEV(J),J=1,NON)
      READ(5,1004) NOF, (OFLEV(J),J=1,NOF)
 1004 FORMAT(I5,10F5.0)
      READ(5,1005) START,STEP,PCF
 1005 FORMAT(8F10.0)
      READ(5,1001) RBAR,(REL(I),I=1,12)
      READ(5,1006) (RLOSS(J),J=1,12)
      READ(5,1003) (SA(J),J=1,NPRC)
      WRITE(6,1110) DEMB,RBAR
 1110 FORMAT(1H0,'DEMB='F8.3,' M.G.D.'/1H ,'RBAR='F8.3,' M.G.D.'/)
C     ORDER SEASONS FROM THE DRIEST TO THE WETTEST
      READ(5,1007) NSN,(MSN(I),I=1,12)
 1006 FORMAT(13F5.0)
 1007 FORMAT(13I5)
      GO TO(4,3,2),NSN
    2 READ(5,1005) ONI2,OFI2,ONI3,OFI3
      GO TO 4
    3 READ(5,1005) ONI2,OFI2
    4 WRITE(6,1012) NSN
 1012 FORMAT(1H0,'THIS IS A'I2,' SEASON RUN')
      IF(NSN.EQ.2) WRITE(6,1013) ONI2,OFI2
 1013 FORMAT(1H ,'WET SEASON ON INC.='F5.2,10X'WET SEASON OFF INC.='F5.2
     1)
      IF(NSN.EQ.3) WRITE(6,1014) ONI2,OFI2,ONI3,OFI3
 1014 FORMAT(1H ,'AVE. SEASON ON INC='F5.3,10X'AVE. SEASON OFF INC='F5.3
     1,/1H ,'WET SEASON ON INC.='F5.3,10X'WET SEASON OFF INC.='F5.3)
      GO TO(1111,1112),IYEAR
 1111 WRITE(6,1015) (MNTH(I),I=1,12),(MSN(I),I=1,12)
 1015 FORMAT(1H0,28X,12A6/1H ,'MONTHLY SEASON ASSIGNMENT'12I6)
      GO TO 1113
 1112 WRITE(6,1015) (MNTHA(I),I=1,12),(MSN(I),I=1,12)
 1113 CONTINUE
      WRITE(6,1016) (DM(I),I=1,12),(REL(J),J=1,12)
 1016 FORMAT(1H0,'DEMAND COEFFICIENTS '5X,12F6.2/1H0,'RELEASE COEFFICIEN
     1TS '4X,12F6.2)
      WRITE(6,1017) (ONLEV(J),J=1,NON)
 1017 FORMAT(1H0,'TURN-ON FRACTIONS'5X,10F5.2)
      WRITE(6,1018) (OFLEV(J),J=1,NOF)
 1018 FORMAT(1H ,'TURN-OFF FRACTIONS'4X,10F5.2)
      WRITE(6,1019) START,STEP,PCF
 1019 FORMAT(1H0,'START='F4.2,/1H ,'STEP='F4.2,/1H ,'PCF='F4.2)
      READ(5,1020) NOLF,(OFACT(J),J=1,NOLF)
      READ(5,1020) NOFF,(FACT(J),J=1,NOFF)
 1020 FORMAT(I2,3X,8F5.0)
      READ(5,1021) (CAPC(J),J=1,NOLF)
 1021 FORMAT(8F10.0)
      WRITE(6,1022)
 1022 FORMAT(1H1,30X,'COST DATA FOR DESALTING PLANT USED IN ANALYSIS')
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      WRITE(5,1023)
      WRITE(6,1024)
 1023 FORMAT(1H0,'OPER. L. F. '5X,'ANNUAL COST IN $/YR. FOR THE PLANT TH
     1AT IS OPTIMIZED AT THE GIVEN LOAD FACTOR (IN PERCENT)')
 1024 FORMAT(1H ,'(IN PERCENT)')
      WRITE(6,1025) (OFACT(J),J=1,NOLF)
 1025 FORMAT(1H0,15X,10F10.0)
      DO 60 J=1,NOLF
      READ(5,1021) (OPCST(I,J),I=1,NOFF)
   60 CONTINUE
      DO 61 I=1,NOFF
   61 WRITE(6,1026) FACT(I),(OPCST(I,J),J=1,NOLF)
 1026 FORMAT(1H0,2X,F5.0,13X,10F10.0)
      READ(5,1021) ETONC,ETOFC,INT,RATF
      WRITE(6,1027) (CAPC(J),J=1,NOLF)
      WRITE(6,1028) RATE
 1027 FORMAT(1H0,'ANNUAL FIXED CHG.'3X,10F10.0)
 1028 FORMAT(1H ,'AT'1X,F5.2,2X,'PERCENT')
      WRITE(6,1029) ETONC,ETOFC,INT
 1029 FORMAT(1H0,'ESTIMATED TURN-ON COST= 'F8.0,/1H ,'ESTIMATED TURN-OFF
     1 COST= 'F8.0,/1H ,'INTEREST RATE= 'F8.4)
C     INITIALIZE PARAMETERS . . . . . . . . . . . . . . .
      GO TO(305,306),KREAD
  305 NR=NON+NOF+1
      READ(5,1005) (AVFY(L),L=1,NR)
      READ(5,1005) (XLF(L),L=1,NR)
  306 UCAP=CMAX-CMIN
      IARG = 799531
      C=.00004356*7.48/12.
      DO 309 I=1,12
      CALL CON(DSCAP,DS,I,IYEAR)
      DSV(I)=DS
  309 CONTINUE
      IF(KREAD.EQ.1) GO TO 312
      DO 5 J=1,NON
    5 ONCON(J)=ONLEV(J)*UCAP+CMIN
      DO 6 J=1,NOF
    6 OFCON(J)=OFLEV(J)*UCAP+CMIN
      CALL RULE(NON,NOF,NOR,NSN,KIO)
      CALL YIELD(NPFY,NYFY,NOR,KIO)
      NR=NOR+1
      DO 8 J=1,NR
      XLF(J)=0.
    8 AVFY(J)=0.
      DO 10 J=1,NR
      DO 9 I=1,NPFY
      XLF(J)=XLF(J)+AVLF(I,J)
      AVFY(J)=AVFY(J)+FY(I,J)
    9 CONTINUE
      XLF(J)=XLF(J)/NPFY
      AVFY(J)=AVFY(J)/NPFY
   10 CONTINUE
      GO TO 310
  312 NX=NPFY
      IF(NPER.GT.NX) NX=NPER
      DO 313 J=1,NX
  313 RS(J)=RAN(IARG)
      DO 314 J=1,NPFY
      NYG=NYFY
  314 CALL GNFLO(NYG,KIP,IFLOW,IYEAR)
  310 DO 311 J=1,NR
  311 AVUC(J)=0.
      WRITE(6,2004)
 2004 FORMAT(1H0,'AVERAGE FIRM YIELD')
      WRITE(6,2005) (AVFY(J),J=1,NR)
 2005 FORMAT(1H ,12F10.2)
      WRITE(6,2007)
 2007 FORMAT(1H0,'AVERAGE LOAD FACTORS')
      WRITE(6,2005) (XLF(J),J=1,NR)
      DO 500 K=1,NDP
      DD=TRDEM(K)
      FYINC(K)=TRDEM(K)-AVFY(1)
      CALL TERP3(NON,NOF,DD,ONLEV)
      KP=NSN*NOF
      L=0
      DO 11 J=1,KP,NSN
      L=L+1
      ONCON(J)=ON(L)*UCAP+CMIN
      OFCON(J)=OFLEV(L)*UCAP+CMIN
      IF(NSN.EQ.1) GO TO 11
      ONCON(J+1)=ONCON(J)-UCAP*ONI2
      OFCON(J+1)=OFCON(J)-UCAP*OFI2
      IF(NSN.EQ.2) GO TO 11
      ONCON(J+2)=ONCON(J)-UCAP*ONI3
      OFCON(J+2)=OFCON(J)-UCAP*OFI3
   11 CONTINUE
      NSIG=0
      KMAX=CMAX*0.5
      KMIN=CMIN*0.5
  391 DO 380 LL=1,12
      DEM=DD*DM(LL)*REL(LL)*RBAR
      CALL CON(DEM,CD,LL,IYEAR)
  380 CMD(LL)=CD
      DO 400 NP=1,NPER
      NY=NYP
      CALL GNFLO(NY,KIP,IFLOW,IYEAR)
      IF(IFLOW.EQ.4) GO TO 382
      CALL QCON(NYP,IYEAR)
  382 DO 300 N=1,NOF
      JJ=NSN*(N-1)+NSN(I)
      M=1
      IF(ON(N).GT.0.0) GO TO 12
      UCFY(NP,N)=9999.
      GO TO 300
   12 KON=0
      LEV=1
      KADD=1
      KCON=0
      RSTOR=RS(NP)
      DO 13 J=1,NYP
      NTON(J)=0
      NTOF(J)=0
   13 CONTINUE
      CALL TERP(CAP,RL,NPPC,RSTOR,RLEV,NSIG)
      IF(NSIG.EQ.1) GO TO 130
      IF(RSTOR.LT.ONCON(JJ)) GO TO 374
      GO TO 375
  374 KADD=2
      KON=1
      NTON(1)=1
      IF(RSTOR.LT.OFCON(JJ))  LEV=2
  375 KF=FORCE
      SDSP=0.
      DELS=5.0
      MM=1
      ID=0
```

```
      LD=1
      DFLAG=1
      ALOSS=0.0
      DO 15 LL=1,NYP
      SSHT(LL)=0.
      DSSP(LL)=0.
      DSPRO(LL)=0.
      NMON(LL)=0
      SSPL(LL)=0.
   15 CONTINUE
      DO 90 J=1,NYP
      DO 80 I=1,12
      JJ=NSN*(N-1)+MSN(I)
      RSP=RSTOR
      DELP=DELS
      M=M+1
      MM=MM+1
      CALL TERP(RL,SA,NPRC,RLEV,SSA,NSIG)
      IF(NSIG.EQ.1) GO TO 131
      EVAP=SSA*RLOSS(I)*C
      DELS=Q(M,1)-CMD(I)-EVAP
      GO TO (17,16),KADD
   16 IF(KCON.LT.11) GO TO 118
      IF(NSN.GT.1) GO TO 116
  115 KADD=1
      NTOF(J)=NTOF(J)+1
      KF=FORCE
      KCON=0
      GO TO 17
  116 IF(MSN(I).GT.1) GO TO 115
  118 DELS=DELS+DSV(I)
      KEND=1
      KF=KF-1
      KCON=KCON+1
      DSPRO(J)=DSPRO(J)+DSV(I)
      SDSP=SDSP+DSV(I)
      NMON(J)=NMON(J)+1
      KON=1
   17 RSTOR=RSTOR+DELS
      IF(RSTOR.LT.CMAX) GO TO 26
      IF(KADD.EQ.2.AND.DELP.LT.0.0) GO TO 219
      GO TO 19
  219 KGO=2
      GO TO 33
   19 DELS=RSTOR-CMAX
      RSTOR=CMAX
      LEV=1
      SSPL(J) = SSPL(J) + DELS
      IF(KON.EQ.0) GO TO 70
      GO TO(18,22),KEND
   18 IF(DELS.LT.SDSP) GO TO 20
      DSSP(J)=DSSP(J)+SDSP
      SDSP=0.
      KEND=2
      GO TO 22
   20 DSSP(J)=DSSP(J)+DELS
      SDSP=SDSP-DELS
   22 GO TO(70,23),KADD
   23 IF(KF)24,24,70
C     ENTER HERE TO TURN OFF THE DESALTING PLANT
   24 KADD=1
      NTOF(J)=NTOF(J)+1
      KF=FORCE
      KCON=0
      GO TO 70
   26 KGO=1
      IF(RSTOR.GT.CMIN) GO TO 30
      IF(CMIN.LT..0005) GO TO 201
      GO TO(201,200), DFLAG
  201 DFLAG=2
      DELS=CMIN-RSTOR
      RSTOR=CMIN
      GO TO 202
  200 LD=LD+1
      IF(CMD(I).LT.Q(M,1)) GO TO 1202
      ALOSS=ALOSS+EVAP
      DELS=CMD(I)-Q(M,1)
      RSTOR=CMIN-ALOSS
      IF(RSTOR.GT.0.) GO TO 202
      RSTOR=0.
      GO TO 202
 1202 DELS=CMIN-RSTOR
  202 CALL TERP(CAP,RL,NPRC,RSTOR,RLEV,NSIG)
      IF(NSIG.EQ.1) GO TO 132
      LEV=2
      SSHT(J)=SSHT(J)+DELS
      IF(I.EQ.12.AND.J.EQ.NYP) GO TO 330
   28 GO TO(38,70),KADD
   30 GO TO (331,330), DFLAG
  330 ID=ID+1
      IF(I.EQ.12.AND.J.EQ.NYP) GO TO 80
      LD=1
      DFLAG=1
      ALOSS=0.0
  331 CALL TERP(CAP,RL,NPRC,RSTOR,RLEV,NSIG)
      IF(NSIG.EQ.1) GO TO 132
      IF(KADD.EQ.1) GO TO 35
   31 IF(DELS) 35,35,32
   32 IF(DELP) 33,33,34
   33 IF(RSP.GT.(SDSP-DSV(I)))GO TO 134
      SDSP=RSP+DSV(I)
  134 GO TO(34,19),KGO
   34 IF(RSTOR.GT.SDSP) GO TO 35
      SDSP=RSTOR
   35 IF(OFCON(JJ).LT.ONCON(JJ)) GO TO 45
      GO TO(37,41),KADD
   37 IF(RSTOR.GT.ONCON(JJ ))GO TO 70
C     ENTER HERE TO TURN ON THE DESALTING PLANT
   38 KADD=2
   40 NTON(J)=NTON(J)+1
      GO TO 70
   41 IF(RSTOR.GT.OFCON(JJ ))GO TO 23
      GO TO 70
   45 IF(RSTOR.LT.ONCON(JJ ))GO TO 53
      GO TO 22
   50 IF(RSTOR.GT.OFCON(JJ ))GO TO 53
      GO TO 55
   53 IF(DELS.LT.0.0) GO TO 55
      GO TO(70,23),KADD
   55 GO TO (38,70),KADD
   70 IF(KPC.NE.1) GO TO 80
   71 KSTO(MM-1)=RSTOR+0.5
   80 CONTINUE
C      AT THIS POINT HAVE COMPLETED ONE YEAR OF THE PERIOD
   90 CONTINUE
C      AT THIS POINT HAVE JUST COMPLETED A PERIOD OF NYP YEARS . . . .
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      GO TO(91,92),KPC
   91 CALL PLOT(KSTO,NYP,KMAX,KMIN)
   92 TEMA=0.
      TEMB=0.
      DO 95 J=1,NYP
      TEMA=TEMA+DSPRO(J)
      TEMB=TEMB+DSSP(J)
   95 CONTINUE
      DSEFF(NP)=(TEMA-TEMB)/TEMA
      GO TO(96,98),KIK
   96 WRITE(6,3000) N,NP
 3000 FORMAT(1H1,'RULE NO.='I2,10X'PERIOD NO.='I2)
      WRITE(6,3001)
 3001 FORMAT(1H0,'        YEAR     TIMES ON   TIMES OFF   MONTHS ON
     1DSPRO         DSSP         SPILL       SHORT.')
      DO 3002 J=1,NYP
 3002 WRITE(6,3003) J,NTON(J),NTOF(J),NMON(J),DSPRO(J),DSSP(J),SSPL(J),
     1SSHT(J)
 3003 FORMAT(4I12,4F12.2)
      WRITE(6,3004) DD,DSEFF(NP)
 3004 FORMAT(1H0,'DEMAND='F8.2,10X'EFFICIENCY='F5.2)
   98 AVELF=AL(N)
      CALL COST(NYP,NP,AVELF,ANCST)
      UCFY(NP,N)=ANCST/(FYINC(K)*365000.)
      GO TO(120,300),KIK
  120 WRITE(6,2000) FYINC(K),ANCST,UCFY(NP,N)
 2000 FORMAT(1H0,'INCREASE IN YIELD='F8.2,' M.G.D.'5X'ANNUAL COST='F10.1
     1,' $/YEAR'5X'UNIT COST OF FYINC='F6.4,' $/K GAL.')
  300 CONTINUE
  400 CONTINUE
C   AVERAGE THE UNIT COST OF THE INCREASE IN FIRM YIELD
      DO 410 J=1,NOF
  403 DO 405 I=1,NPER
      AVUC(J)=AVUC(J)+UCFY(I,J)
  405 CONTINUE
      AVUC(J)=AVUC(J)/NPER
  410 CONTINUE
      WRITE(6,2009)
 2009 FORMAT(1H0,'AVERAGE COSTS FOR FEASIBLE OPERATING RULES')
      WRITE(6,2010) (AVUC(J),J=1,NOF)
 2010 FORMAT(1H ,10F12.4)
C     FIND THE LOWEST AVERAGE UNIT COST OF FYINC
      CALL FIND(AVUC,NOF,IX)
      WRITE(6,3005) AVUC(IX)
 3005 FORMAT(1H1,'MINIMUM COST OF FYINC='F7.4,' $/K GAL.')
      WRITE(6,3006) FYINC(K)
 3006 FORMAT(1H0,'INCREASE IN FIRM YEILD='F7.2,' M.G.D.')
      WRITE(6,3007)  ON(IX),OFLEV(IX)
 3007 FORMAT(1H0,'TURN ON='F6.2,10X'TURN OFF='F6.2)
      OFAC(K)=AL(IX)
      ONOPT(K)=ON(IX)
      OFOPT(K)=OFLEV(IX)
  500 CONTINUE
      STOP
  130 WRITE(6,4000) RSTOR
 4000 FORMAT(1H0,'START=' F10.2)
  900 STOP
  131 WRITE(6,4002) RLEV
 4002 FORMAT(1H0,'RLEV=' F10.2)
      STOP
  132 WRITE(6,4001) RSTOR
 4001 FORMAT(1H0,'RSTOR=' F10.2)
      STOP
      END

      SUBROUTINE YIELD(NOP,NYP,NOR,KIO)
      COMMON /BLOCKA/Q(1201,5)
      COMMON /BLOCKB/ONCON(100),OFCON(100),UCAP
      COMMON /BLOCKC/CAP(100),RL(100),DM(12),RS(50),SA(100),RLOSS(12),
     1REL(12),MSN(12),DSV(12),SSHT(100),CMD(12),FY(20,50),AVLF(20,50),
     2CMAX,NPRC,DSCAP,FORCE,START,STEP,PCF,NSN,DEMB,CMIN,KIP,RBAR,
     3KREAD,ISTOR,IFLOW,IYEAR,NPER
      DIMENSION KON(20),IDD(20),DLEV(20),NMON(100),STOT(20),KFREQ(20),
     1ALOAD(20),TS(20),PI(20),AVDUR(20),KDUR(250),RCON(100)
      INTEGER FORCE,DFLAG
      NYPSV=NYP
      PPCF=PCF*100.
      IARG=798531
      C=.00004356*7.48/12.
      RS(1)=CMIN+0.5*UCAP
      KSTRT=1
      DO 300 NP=1,NOP
C     GENERATE NYP YEARS OF STREAMFLOW AND CONVERT RATES TO VOLUMES  *  *  *
      NYG=NYP
      IF(NP.EQ.1.AND.NYP.LT.75) NYG=75
      CALL GNFLO(NYG,KIP,IFLOW,IYEAR)
      IF(IFLOW.EQ.4) GO TO 11
      IF(NP.EQ.1.AND.NYP.LT.75) NYP=75
      CALL QCON(NYP,IYEAR)
      NYP=NYPSV
   11 JJ=MSN(1)
      DBAR=DEMB
      NR=NOR+1
      DO 200 N=1,NR
      II=0
      KNT=1
      KCON=0
      MG=0
      ML=0
      MCK=0
      IF (N.NE.1) GO TO 17
      SSTART=START-0.20
      GO TO 18
   17 SSTART=START
C     MODIFY THE STARTING DEVELOPMENT LEVEL DEPENDING ON THE RULE **  **  **
      JJ=NSN*(N-2)+1
      TESTA=0.5*UCAP+CMIN
      IF(ONCON(JJ).GT.TESTA) SSTART=START+0.35
      IF(ONCON(JJ).LT.TESTA) SSTART=START-0.35
      IF(ONCON(JJ).LT.TESTA.AND.OFCON(JJ).LT.TESTA) SSTART=START-0.10
      IF(ONCON(JJ).LT.0.3*UCAP+CMIN) SSTART=START-0.15
   18 IK=0
      SINC=STEP
      IKNT=0
      IF(II.EQ.0) GO TO 21
   20 SSTART=SSTART-SINC
   21 IF(KNT.GT.11) GO TO 903
      M=1
      II=II+1
      KNT=KNT+1
      DLEV(II)=SSTART
  321 DD=DBAR*DLEV(II)
C     CONVERT THE DEMAND RATES TO VOLUMES  *  *  *  *  *  *  *  *
  322 DO 22 I=1,12
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      DEM=DD*DM(I)+REL(I)*RBAR
      CALL CON(DEM,CD,I,IYEAR)
      CMD(I)=CD
   22 CONTINUE
      LEV=1
      KADD=1
      KON(II)=0
      RSTOR=RS(NP)
      CALL TERP(CAP,RL,NPRC,RSTOR,RLEV,NSIG)
      IF(NSIG.EQ.1) GO TO 901
      IF(N.EQ.1) GO TO 30
      IF(RSTOR.GT.ONCON(JJ)) GO TO 23
      KADD=2
      KCON=1
      KON(II)=1
   23 IF(RSTOR.LT.OFCON(JJ)) LEV=2
   30 KF=FORCE
      ID=0
      LD=1
      DFLAG=1
      ALOSS=0.0
      IDD(II)=0
      KDUR(1)=0
      DO 31 J=1,NYP
      SSHT(J)=0.
      NMON(J)=0
   31 CONTINUE
      DO 90 J=1,NYP
      DO 80 I=1,12
      IF(N.EQ.1) GO TO 32
      JJ=NSN*(N-2)+MSN(I)
      IF(I.EQ.12) GO TO 32
      JJ=NSN*(N-2)+MSN(I+1)
   32 M=M+1
      CALL TERP(RL,SA,NPRC,RLEV,SSA,NSIG)
      IF(NSIG.EQ.1) GO TO 902
      EVAP=SSA*RLOSS(I)*C
      DELS=Q(M,1)-CMD(I)-EVAP
      GO TO(36,35),KADD
   35 IF(KCON.LT.11) GO TO 338
      IF(NSN.GT.1) GO TO 336
  335 KADD=1
      KCON=0
      GO TO 36
  336 IF(MSN(I).GT.1) GO TO 335
  338 DELS=DELS+DSV(I)
      KF=KF-1
      KCON=KCON+1
      NMON(J)=NMON(J)+1
   36 RSTOR=RSTOR+DELS
      IF(RSTOR.LT.CMAX) GO TO 50
   40 DELS=RSTOR-CMAX
      RSTOR=CMAX
      LEV=1
   42 GO TO(80,44),KADD
   44 IF(KF) 46,46,80
   46 KADD=1
      KF=FORCE
      KCON=0
      GO TO 80
   50 IF(RSTOR.GT.CMIN) GO TO 56
      IF(CMIN.LT..0005) GO TO 54
      GO TO(54,53),DFLAG
   54 DFLAG=2
      DELS=CMIN-RSTOR
      RSTOR=CMIN
      GO TO 55
   53 LD=LD+1
      IF(CMD(I).LT.Q(M,1)) GO TO 155
      ALOSS=ALOSS+EVAP
      DELS=CMD(I)-Q(M,1)
      RSTOR=CMIN-ALOSS
      IF(RSTOR.GT.0.) GO TO 55
      RSTOR=0.
      GO TO 55
  155 DELS=CMIN-RSTOR
   55 CALL TERP(CAP,RL,NPRC,RSTOR,RLEV,NSIG)
      IF(NSIG.EQ.1) GO TO 901
      LEV=2
      SSHT(J)=SSHT(J)+DELS
      IF(I.EQ.12.AND.J.EQ.NYP) GO TO 57
      IF(N.EQ.1) GO TO 80
      GO TO(65,80),KADD
   56 GO TO(59,57),DFLAG
   57 ID=ID+1
      IDD(II)=ID
      KDUR(ID)=LD
      IF(I.EQ.12.AND.J.EQ.NYP) GO TO 90
      LD=1
      DFLAG=1
      ALOSS=0.0
C     OBTAIN THE NEW RESERVOIR LEVEL  . . . . . . . . . .
   59 CALL TERP(CAP,RL,NPRC,RSTOR,RLEV,NSIG)
      IF(NSIG.EQ.1) GO TO 901
   62 IF(N.EQ.1) GO TO 80
      IF(OFCON(JJ).LT.ONCON(JJ)) GO TO 70
      GO TO(64,68),KADD
   64 IF(RSTOR.GT.ONCON(JJ)) GO TO 80
   65 KADD=2
      KON(II)=KON(II)+1
      GO TO 80
   68 IF(RSTOR.GT.OFCON(JJ)) GO TO 44
      GO TO 80
   70 IF(RSTOR.LT.ONCON(JJ)) GO TO 72
      GO TO 42
   72 IF(RSTOR.GT.OFCON(JJ)) GO TO 73
      GO TO 75
   73 IF(DELS.LT.0.0) GO TO 75
      GO TO(80,44),KADD
   75 GO TO(65,80),KADD
   80 CONTINUE
      IF(KSTRT.NE.2) GO TO 90
      RCON(J)=RSTOR
C     AT THIS POINT HAVE JUST COMPLETED ONE YEAR OF THE PERIOD  . . . .
   90 CONTINUE
C     AT THIS POINT HAVE JUST COMPLETED A PERIOD OF NYP YEARS  . . . .
      IF(KSTRT.NE.2) GO TO 96
      NN=NPFY
      IF(NPER.GT.NPFY) NN=NPER
      DO 92 L=1,NN
      XNUM=RAN(IARG)*50.0+0.5
      NUM=XNUM
      NUM=NUM+25
      RS(L)=RCON(NUM)
   92 CONTINUE
      KSTRT=1
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      NYP=NYPSV
      GO TO 190
   96 STOT(II)=0.0
      KFREQ(II)=0
      TLOAD=0.
      YRK=0.
      DO 100 J=1,NYP
      IF(NMON(J).EQ.0) GO TO 97
      YRK=YRK+1.0
      AA=NMON(J)
      TLOAD=TLOAD+AA/12.
   97 IF(SSHT(J).GT.0.0) GO TO 98
      GO TO 100
   98 KFREQ(II)=KFREQ(II)+1
      STOT(II)=STOT(II)+SSHT(J)
  100 CONTINUE
      ALOAD(II)=TLOAD/YRK*100.
      YDEM=DBAR*DLEV(II)*.365
      XNYP=NYP
      XF=KFREQ(II)
      TS(II)=(1.0-XF/XNYP)*100.
  104 PI(II)=(1.0-STOT(II)/(XNYP*YDEM))*100.
      KSUM=0
      DO 120 IX=1,ID
      KSUM=KSUM+KDUP(IX)
  120 CONTINUE
      SUM=KSUM
      XID=ID
      AVDUR(II)=SUM/XID
      IF(PPCF.GT.99.9) GO TO 500
      IF(TS(II).GT.64.0) GO TO 121
      SSTART=SSTART-2.0*SINC
      GO TO 21
  121 IF(TS(II).GT.PPCF) GO TO 125
      IF(TS(II).LT.PPCF-1.0) GO TO 122
      FY(NP,N)=DD
      AVLF(NP,N)=ALOAD(II)
      GO TO 139
  122 IKNT=IKNT+1
      IF(IK.GT.0.AND.IKNT.GT.1) SINC=0.8*SINC
      GO TO 20
  125 IF(TS(II).LT.100.0.AND.II.GT.1) GO TO 131
      IF(II.EQ.1) GO TO 133
      IF(IK.EQ.3) GO TO 131
      IK=IK+1
      IKNT=0
      SINC=SINC/2.0
  133 SSTART=SSTART+SINC
      II=II-1
      GO TO 21
  131 NPTS=II-1
      DO 132 I=1,NPTS
      L=I
      IF(TS(I).LE.PPCF.AND.TS(I+1).GE.PPCF) GO TO 135
  132 CONTINUE
      WRITE(6,4000)
 4000 FORMAT(1H1,'PCF TEST NOT IN RANGE')
      GO TO 999
  135 FY(NP,N)=(DBAR*(DLEV(L)-DLEV(L+1)))*(TS(L+1)-PPCF)/(TS(L+1)-TS(L))
     1+DBAR*DLEV(L+1)
      AVLF(NP,N)=(ALOAD(L)+ALOAD(L+1))/2.
      GO TO 139
  500 IF(SINC.LT.0.005.OR.MCK.EQ.2) GO TO 512
      WRITE(6,6000) TS(II),SSTART,SINC,KFREQ(II),DD
 6000 FORMAT(1H ,3F15.2,I10,F15.2)
      IF(TS(II).GT.85.0.OR.MG.NE.0) GO TO 501
      ML=1
      SSTART=SSTART-2.0*SINC
      GO TO 21
  501 IF(TS(II).LT.99.9) GO TO 505
C     ENTER HERE IF TS(II) EQUAL 100 PERCENT
      MG=1
      IF(ML.EQ.0) GO TO 502
      MCK=MCK+1
      IISAV=II
      DDSAV=DD
      SINC=SINC/2.0
  502 SSTART=SSTART+SINC
      GO TO 21
C     ENTER HERE IF TS(II) IS LESS THAN 100 PERCENT
  505 ML=1
      IF(MG.GT.0) SINC=SINC/2.0
      GO TO 20
  512 IF(TS(II).GT.99.9) GO TO 515
      DD=DDSAV
      II=IISAV
  515 FY(NP,N)=DD
      AVLF(NP,N)=ALOAD(II)
  139 GO TO (140,189),KIO
  140 IF(N.GT.1) GO TO 142
      WRITE(6,3000)
 3000 FORMAT(1H1,'OPERATION WITHOUT THE DESALTING PLANT')
      GO TO 147
  142 KP=NSN*(N-2)+1
      WRITE(6,3001) ONCON(KP),OFCON(KP)
 3001 FORMAT(1H0,'OPERATING RULE'/1H ,'SEASON 1, ON='F6.2,' B.G.'10X'OFF
     1='F6.2,' B.G.')
      IF(NSN.EQ.1) GO TO 147
      KP=KP+1
  145 WRITE(6,3002) ONCON(KP),OFCON(KP)
 3002 FORMAT(1H ,'SEASON 2, ON='F6.2,' B.G.'10X'OFF='F6.2,' B.G.')
      IF (NSN.EQ.2) GO TO 147
      KP=KP+1
      WRITE (6,3103) ONCON(KP),OFCON(KP)
 3103 FORMAT(1H ,'SEASON 3, ON='F6.2,' B.G.'10X'OFF='F6.2,' B.G.')
  147 WRITE(6,3003)
 3003 FORMAT(1H0,'     PERCENT       DEMAND    NO. OF       SHORTAGES    FREQ
     1UENCY PERFORMANCE     SHORTAGE        PLANT')
 3004 FORMAT(1H ,'       DEMAND        M.G.D.    SHORTAGES      B.G.       OF T
     1ARGET     INDEX        DURATION       TURN ON       ALOAD'/)
      WRITE(6,3004)
  150 DO 160 I=1,II
      RD=DBAR*DLEV(I)
      WRITE(6,3005) DLEV(I),RD,KFREQ(I),STOT(I),TS(I),PI(I),AVDUR(I),
     1KON(I),ALOAD(I)
 3005 FORMAT(2F12.2,I12,F12.2,3F12.2,I12,F12.2)
  160 CONTINUE
  189 IF(KSTRT.NE.1.OR.N.GT.1.OR.NP.GT.1) GO TO 190
      KSTRT=2
      NYP=75
      M=1
      DD=FY(1,1)
      GO TO 322
  190 IF(N.EQ.1) DBAR=DBAR+DSCAP
  200 CONTINUE
C     AT THIS POINT HAVE COMPLETED ONE PERIOD FOR ALL RULES   .   .   .   .
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  300 CONTINUE
C     AT THIS POINT HAVE COMPLETED NOP PERIODS OF NYP YEARS    .    .    .    .
      GO TO(301,350),KIO
  301 DO 310 J=1,NP
      WRITE(6,3010) J,(FY(L,J),L=1,NOP)
 3010 FORMAT(1H0,'RULE NUMBER'I3/1H ,(12F10.4))
  310 CONTINUE
  350 RETURN
  901 WRITE(6,4001)
 4001 FORMAT(1H1,'RLEV NOT IN RANGE OF TABLE')
      GO TO 999
  902 WRITE(6,4002)
 4002 FORMAT(1H1,'SSA NOT IN RANGE OF TABLE')
      GO TO 999
  903 WRITE(6,4003)
 4003 FORMAT(1H1,'SSTART LES THAN ZERO OR II GREATER THAN 10')
  999 STOP
      END


      SUBROUTINE COST(NYP,NP,AVEL,ANCST)
      COMMON /BLOCKD/NTON(50),NTOF(50),NMON(50),FACT(10),CAPC(10),OPCST(
     110,10),OFACT(10),NOLF,NOFF,ETONC,ETOFC,INT,RATE
      REAL INT
      IF(AVEL.GT.OFACT(1)) GO TO 12
      J=1
      GO TO 20
   12 IF(AVEL.LT.OFACT(NOLF)) GO TO 14
      J=NOLF
      GO TO 20
   14 DO 18 I=1,NOLF
      IF(OFACT(I+1).LT.AVEL) GO TO 18
C   ENTER HERE IF AVEL FALLS BETWEEN OFACT(I) AND OFACT(I+1)
      IF(AVEL-OFACT(I).LT.OFACT(I+1)-AVEL) GO TO 17
      J=I+1
      GO TO 20
   17 J=I
      GO TO 20
   18 CONTINUE
   20 PWTH=0.
C    ANNUALIZE THE OPERATING EXPENSES
      DO 40 L=1,NYP
      TEM=ETONC*NTON(L)+ETOFC*NTOF(L)
      AA=NMON(L)
      XLF=AA/12.0*100.0
C  DO TABLE LOOK-UP WITH INTERPOLATION(LINEAR TO OBTAIN COST($/YEAR)
      IF(XLF.GT.0.) GO TO 22
      CST=OPCST(1,J)
      GO TO 30
   22 IF(XLF.LT.95.0) GO TO 25
      CST=OPCST(NOFF,J)
      GO TO 30
   25 DO 27 I=1,NOFF
      IF(XLF.GT.FACT(I+1)) GO TO 27
C    ENTER HERE IF XLF FALLS BETWEEN FACT(I) AND FACT(I+1)
      FRAC=(XLF-FACT(I))/(FACT(I+1)-FACT(I))
      CST=OPCST(I,J)+FRAC*(OPCST(I+1,J)-OPCST(I,J))
      GO TO 30
   27 CONTINUE
C   DISCOUNT THE COSTS FOR THE L TH YEAR TO THE PRESENT
   30 FAC=(1.0+INT)**L
      PWTH=PWTH+(CST+TEM)/FAC
   40 CONTINUE
C   APPLY CAPITAL RECOVERY FACTOR TO OBTAIN UNIFORM SERIES
      USER=PWTH*INT*FAC/(FAC-1.0)
      ANCST=USER+CAPC(J)
      RETURN
      END


      SUBROUTINE TERP3(NON,NOF,TRDEM,ONLEV)
      COMMON /BLOCKE/ AVFY(50),XLF(50),ON(10),AL(10)
      DIMENSION ONLEV(10)
      DO 5 J=1,NOF
      ON(J)=0.
    5 CONTINUE
    1 DO 60 L=1,NOF
      DO 50 J=1,NON
      I=NOF*(J-1)+L+1
      IF(AVFY(I).LT.TRDEM) GO TO 48
      IF(J.NE.NON) GO TO 50
   45 DIFF=AVFY(I)-TRDEM
      IF(DIFF.GT.0.02*TRDEM) GO TO 50
      ON(L)=ONLEV(J)
      AL(L)=XLF(I)
      GO TO 60
   48 IF(J.EQ.1) GO TO 52
      GO TO 57
   52 DIFF=TRDEM-AVFY(I)
      IF(DIFF.GT.0.02*TRDEM) GO TO 55
      ON(L)=ONLEV(J)
      AL(L)=XLF(I)
      GO TO 60
   57 ON(L)=ONLEV(J)+(TRDEM-AVFY(I))/(AVFY(I-NOF)-AVFY(I))*(ONLEV(J-1)-
     1ONLEV(J))
      AL(L)=XLF(I)+(ON(L)-ONLEV(J))/(ONLEV(J-1)-ONLEV(J))*(XLF(I-NOF)-
     1XLF(I))
      GO TO 60
   50 CONTINUE
      WRITE(6,2000) L
 2000 FORMAT(1H0,'MINIMUM VALUE OF CURVE'I2,' GREATER THAN TRDEM')
      GO TO 60
   55 WRITE(6,2001) L
 2001 FORMAT(1H0,'MAXIMUM VALUE OF CURVE'I2,' LESS THAN TRDEM')
   60 CONTINUE
      WRITE(6,2012)
 2012 FORMAT(1H1,'INTERPOLATED TURN-ON FRACTIONS')
      WRITE(6,2002) (ON(I),I=1,NOF)
      WRITE(6,2013)
 2013 FORMAT(1H0,'INTERPOLATED AVERAGE LOAD FACTORS')
      WRITE(6,2003) (AL(I),I=1,NOF)
 2002 FORMAT(1H ,10F12.3)
 2003 FORMAT(1H ,13F10.2)
      RETURN
      END
      FUNCTION RAN (IARG)
      DATA IX/0/
      IF (IARG.EQ.IX) GO TO 3
      IX=IARG
      IY=IX
    3 IY=IY*262147
      IF(IY.LT.0) IY=IY+34359738367+1
      RAN=IY
      RAN=RAN*.2910383E-10
```

```
      RETURN
      END


      SUBROUTINE FIND(AA,N,IX)
      DIMENSION AA(50)
C THIS SUBROUTINE FINDS THE MINIMUM COST OF THE INCREASE IN FIRM YIELD*
    1 AMIN=99999.
      DO 20 J=1,N
      IF(AA(J).GT.AMIN) GO TO 20
      AMIN=AA(J)
      IX=J
   20 CONTINUE
      RETURN
      END


      SUBROUTINE QCON(NY,IYEAR)
      COMMON /BLOCKA/Q(1201,5)
      M=1
      DO 8 J=1,NY
      DO 8 I=1,12
      M=M+1
      SUP=Q(M,1)
      CALL CON(SUP,CS,I,IYEAR)
      Q(M,1)=CS
    8 CONTINUE
      RETURN
      END


      SUBROUTINE CON(VAL,CVAL,K,IYEAR)
      GO TO(10,11),IYEAR
   10 GO TO(1,3,1,1,2,1,3,1,3,1,1,3),K
   11 GO TO(1,2,1,3,1,3,1,1,3,1,3,1),K
    1 CVAL=.031*VAL
      GO TO 5
    2 CVAL=.028*VAL
      GO TO 5
    3 CVAL=.030*VAL
    5 RETURN
      END


      SUBROUTINE PLOT(MSTOR,NY,NFULL,NEMPT)
      DIMENSION NARR(120),MA(120),OUT(120),MSTOR(360)
      DATA BK/1H /,X/1H*/
      NKNT=NY*12
      DO 2 I=1,NKNT
      MSTOR(I)=(MSTOR(I)*100)/NFULL
      TEM=MSTOR(I)
      TEM=TEM/2.0
      NTEM=TEM
      ATEM=NTEM
      IF(TEM-ATEM.NE.0.0) MSTOR(I)=MSTOR(I)+1
    2 CONTINUE
      FLTN=NY
      TEM=FLTN/10.+0.5
      NN=TEM
      DO 30 II=1,NN
      KK=120
      LL=(II-1)*10
      IF((NY-LL).LT.10) KK=LL*12
      JA=(II-1)*120
      DO 5 JJ=1,KK
      NARR(JJ)=MSTOR(JJ+JA)
      MA(JJ)=JJ
    5 CONTINUE
C     RANK VALUES IN DESCENDING ORDER
      N=KK
      M=N
    J M=M/2
      IF(M) 10,20,10
   10 K=N-M
      J=1
   11 I=J
   12 L=I+M
      IF(NARR(L)-NARR(I)) 16,16,15
   15 NB=NARR(L)
      NA=MA(L)
      NARR(L)=NARR(I)
      MA(L)=MA(I)
      NARR(I)=NB
      MA(I)=NA
      I=I-M
      IF(I-1)16,12,12
   16 J=J+1
      IF(J-K)11,11,9
   20 WRITE(6,1000) NFULL,NEMPT,II
 1000 FORMAT(1H1,'CAPACITY WHEN FULL='I6,' B.G.',4X,'CAPACITY AT MIN. US
     1ABLE LEVEL='I4,' B.G.'/1H ,'ORDINATE(RESERVOIR CONTENT) IS IN PERC
     2ENT',20X,'PAGE='I2/)
      KORD=100
      K=1
      IX=1
      DO 28 I=1,51
      IF(I.NE.IX) GO TO 22
      NORD=(51-IX)*2
      IX=IX+5
      WRITE(6,1002) NORD
 1002 FORMAT(1H ,I3,1H-)
      GO TO 122
   22 WRITE(6,1003)
 1003 FORMAT(1H ,3X,1H-)
  122 DO 23 J=1,120
   23 OUT(J)=BK
   24 IF(K.GT.KK) GO TO 26
      IF(NARR(K).NE.KORD) GO TO 25
      L=MA(K)
      OUT(L)=X
      K=K+1
      GO TO 24
   25 KORD=KORD-2
   26 WRITE(6,1001) (OUT(J),J=1,120)
 1001 FORMAT(1H+,6X,120A1)
   28 CONTINUE
   30 CONTINUE
   35 RETURN
      END
```

```
      SUBROUTINE TERP(A,B,NPTS,ARG,VAL,NSIG)
C     THIS SUBROUTINE ASSUMES THAT THE B ARRAY IS NONDECREASING AS THE
C     A ARRAY INCREASES.
      DIMENSION A(100),B(100)
      IF(ARG.LT.A(1).OR.ARG.GT.A(NPTS)) GO TO 30
      IF(ARG.NE.A(NPTS)) GO TO 10
      VAL=ARG
      GO TO 50
   10 DO 20 I=1,NPTS
      IF(ARG.GE.A(I)) GO TO 20
      VAL=B(I-1)+(B(I)-B(I-1))*(ARG-A(I-1))/(A(I)-A(I-1))
      GO TO 50
   20 CONTINUE
      GO TO 50
   30 WRITE(6,40)
   40 FORMAT(1H0,'THE ARGUMENT IS OUT OF THE RANGE OF THE RESERVOIR DATA
     1')
      NSIG=1
   50 RETURN
      END


      SUBROUTINE RULE(NON,NOF,NOR,NSN,KIO)
      COMMON /BLOCKB/ONCON(100),OFCON(100),UCAP
      COMMON /BLOCKF/ONI2,OFI2,ONI3,OFI3
      DIMENSION RUL(25,2)
C
C   THIS ROUTINE FORMULATES THE RULES THAT CONSTITUTE THE DECISION SPACE ** ** *
      KM=0
      DO 5 I=1,NON
      DO 5 J=1,NOF
      KM=KM+1
      RUL(KM,1)=ONCON(I)
      RUL(KM,2)=OFCON(J)
    5 CONTINUE
      KP=NSN*KM
      IF(NSN.EQ.1) GO TO 15
      DON2=ONI2*UCAP
      DOF2=OFI2*UCAP
      IF(NSN.EQ.2) GO TO 15
      DON3=ONI3*UCAP
      DOF3=OFI3*UCAP
      IF(NSN.NE.3) GO TO 900
   15 NOR=KM
      L=0
      DO 20 I=1,KP,NSN
      L=L+1
      ONCON(I)=RUL(L,1)
      OFCON(I)=RUL(L,2)
      IF(NSN.EQ.1) GO TO 20
      ONCON(I+1)=ONCON(I)- DON2
      OFCON(I+1)=OFCON(I)- DOF2
      IF(NSN.EQ.2) GO TO 20
      ONCON(I+2)=ONCON(I)-DON3
      OFCON(I+2)=OFCON(I)-DOF3
   20 CONTINUE
      GO TO (21,22),KIO
   21 WRITE(6,1005) (ONCON(J),OFCON(J),J=1,KP)
 1005 FORMAT(1H1,'OPERATING RULES'//(1X ,10F10.2))
   22 RETURN
  900 WRITE(6,2000)
 2000 FORMAT(1H1,'NUMBER OF SEASONS SPECIFIED IS IN ERROR')
      STOP


      SUBROUTINE GNFLO(NYRG,KIP,IFLOW,IYEAR)
C     FIVE STATION VERSION DIMENSIONED FOR 100 YEARS
      COMMON /BLOCKA/Q(1201,5)
      DIMENSION ALCFT(12,5),AV(12,5),BETA(12,5,5),DQ(12,5),IQ(15),
     1ISTA(5),MO(12),NCAB(12,5),NLOG(12,5),            QM(12),QPREV(10),
     2R(10,11),RA(12,5,10),SD(12,5),SKEW(13,5),SQA(12,10),SQB(12,10),
     3SUMA(12,10),SUMB(12,10),X(10),XPAB(12,10),          NLG(12,5),AVG(12
     4,5),SDV(12,5),AA(12,5,10),AB(12,5,10),AC(10),B(20),QR(1201,5)
C     23-C4-L267 MONTHLY STREAMFLOW SIMULATION HEC, C OF E, USA  8-18-67
C INDEXES I=CALENDAR MONTH J=YEAR K=STA L=RELATED STA M=SUCCESSIVE MONTH
C
      DOUBLE PRECISION R,B
      DATA LTRA/1HA/,BLANK/1H /,E/1HE/,KENT/1/
      NYRIG=NYRG
      IF(KENT.EQ.2) GO TO 101
      KENT=2
  101 IARG=798531
      KSTA=1
      KYR=100
      KM=KYR*12+1
      IENDF=0
      IDGST=0
    1 FORMAT(1X,I7,9I8)
    2 FORMAT(1X,A3,9A4,10A4,
    3 FORMAT(1H0)
    4 FORMAT(I6,4X,I4,12F5.0)
    6 FORMAT(1X,I3,I4,12I6)
    7 FORMAT(1X,I3,I4,12F6.3)
C                WASTE CARDS UNTIL AN A IN COLUMN 1, FIRST TITLE CARD
   10 READ(5,12) IA,(Q(M,1),M=1,20)
      IF (IA.NE.LTRA) GO TO 10
      IF(IENDF.GT.0) GO TO 1271
      IENDF=IENDF+1
   11 FORMAT(1H ,I4,I6,12I8,I10)
   12 FORMAT (A1,A3,9A4,10A4)
      WRITE(6,3)
      IF(KIP.EQ.2) GO TO 13
      WRITE(6,2)   (Q(M,1),M=1,20)
   13 READ(5,1) IYRA,IMNTH,IMSNG,ITEST,IRCON,NSTA,IPCHQ
      ITMP=IRCON+NYRG
      IF(ITMP.GT.0)GO TO 30
      GO TO 10
   20 WRITE (6,25)
      STOP
   25 FORMAT(/19H DIMENSION EXCEEDED)
   30 IF(KIP.EQ.2) GO TO 42
      WRITE(6,40)
   40 FORMAT(1H0,'IYRA  IMNTH IMSNG ITEST IRCON NYRG  NSTA  IPCHQ NYRIG'
     1)
      WRITE(6,41) IYRA,IMNTH,IMSNG,ITEST,IRCON,NYRG,NSTA,IPCHQ,NYRIG
   41 FORMAT (20I6)
C                SET CONSTANTS
   42 T=99999999.
      TM=T-1.0
      IYRA=IYRA-1
      IMNTH=IMNTH-1
      DO 50 I=1,12
      ITMP=KSTA+2
      DO 46 K=1,KSTA
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      DO 45 L=1,ITMP
      AA(I,K,L)=0.
   45 AB(I,K,L)=0.
   46 CONTINUE
      MO(I)=IMNTH+I
      IF(MO(I).LT.13)GO TO 50
      MO(I)=MO(I)-12
   50 CONTINUE
   58 NYRS=0
      DO 70 K=1,KSTA
      ISTA(K)=1000-K
C              INITIATE -1, NO RECORD FOR ALL FLOWS
      DO 60 M=1,KM
   60 Q(M,K)=-1.
      DO 65 I=1,12
      NLOG(I,K)=0
      DQ(I,K)=0.
   65 CONTINUE
   70 CONTINUE
C  . . . . . . READ AND PROCESS 1 STATION-YEAR OF DATA . . . . . . . . . . . . . .
      NSTA=0
   75 READ(5,4)ISTAN,IYR,(QM(I),I=1,12)
C              BLANK CARD INDICATES END OF FLOW DATA
   78 IF(ISTAN.LT.1)GO TO 130
      IF(NSTA.LT.1)GO TO 97
C              ASSIGN SUBSCRIPT TO STATION
      DO 80 K=1,NSTA
      IF(ISTAN.EQ.ISTA(K))GO TO 100
   80 CONTINUE
   90 NSTA=NSTA+1
      K=NSTA
      ISTA(K)=ISTAN
C              ASSIGN SUBSCRIPT TO YEAR
  100 J=IYR-IYRA
      IF(NYRS.LT.J)NYRS=J
      IF(J.GT.0)GO TO 110
      WRITE (6,105)IYR
  105 FORMAT (/18H UNACCEPTABLE YEAR I5)
      STOP
C              STORE FLOWS IN STATION AND MONTH ARRAY
  110 M=J*12-11
      DO 120 I=1,12
      M=M+1
      IZ=QM(I)
      IF(IZ.EQ.-1) GO TO 120
      NLOG(I,K)=NLOG(I,K)+1
      GO TO(506,507,501,507),IFLOW
  501 GO TO(511,512),IYEAR
  511 GO TO(502,503,502,502,504,502,503,502,503,502,502,503),I
  512 GO TO(502,504,502,503,502,503,502,502,503,502,503,502),I
  502 QM(I)=QM(I)*0.3226
      GO TO 505
  503 QM(I)=QM(I)*0.3333
      GO TO 505
  504 QM(I)=QM(I)*0.3571
  505 QM(I)=QM(I)*0.50505
C     CONVERT C.F.S. TO M.G.D.
  506 QM(I)=QM(I)*0.64627
  507 DQ(I,K)=DQ(I,K)+QM(I)
      Q(M,K)=QM(I)
  120 CONTINUE
      GO TO 75
  130 NSTAA=NSTA+1
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```
      IF(NYRS.GT.KYR) GO TO 20
      NSTAX=NSTA+NSTA
C  . . . . . . COMPUTE FREQUENCY STATISTICS . . . . . . . . . . . . . . . . . . .
      GO TO(131,316),KIP
  131 WRITE(6,314)
  314 FORMAT (/21H FREQUENCY STATISTICS)
      WRITE(6,315)(MO(I),I=1,12)
  315 FORMAT(/14H    STA     ITEM I7,11I8)
C              MISSING FLOW PRECEDING FIRST RECORD MONTH
  316 DO 317 K=1,NSTA
      Q(1,K)=T
  317 CONTINUE
      DO 421 K=1,NSTA
  318 DO 320 I=1,12
      AV(I,K)=0.
      SD(I,K)=0.
      SKEW(I,K)=0.
      TEMP=NLOG(I,K)
      DQ(I,K)=DQ(I,K)*.012/TEMP
      IF(DQ(I,K).LT..01)DQ(I,K)=.01
  320 CONTINUE
      M=1
      DO 350 J=1,NYRS
      DO 340 I=1,12
      M=M+1
      IZ=Q(M,K)
      IF(IZ.EQ.-1) GO TO 330
C              REPLACE FLOW ARRAY WITH LOG ARRAY
      TEMP=ALOG(Q(M,K)+DQ(I,K))/2.3026
      Q(M,K)=TEMP
C              SUM, SQUARES, AND CUBES
      AV(I,K)=AV(I,K)+TEMP
      SD(I,K)=SD(I,K)+TEMP*TEMP
      SKEW(I,K)=SKEW(I,K)+TEMP*TEMP*TEMP
      GO TO 340
C              MISSING FLOWS EQUATED TO T
  330 Q(M,K)=T
  340 CONTINUE
  350 CONTINUE
      DO 360 I=1,12
      TEMP=NLOG(I,K)
      TMP=AV(I,K)
      AV(I,K)=TMP/TEMP
      IF(SD(I,K).LE.0.)GO TO 355
      TMPA=SD(I,K)
      SD(I,K)=(SD(I,K)-AV(I,K)*TMP)/(TEMP-1.)
      SD(I,K)=SD(I,K)**.5
      SKEW(I,K)=(TEMP*TEMP*SKEW(I,K)-3.*TEMP*TMP*TMPA+2.*TMP*[illegible]
     1/(TEMP*(TEMP-1.)*(TEMP-2.)*SD(I,K)**3.)
      IF (SKEW(I,K).GT.5.) SKEW(I,K)=5.
      IF (SKEW(I,K).LT.(-5.)) SKEW(I,K)=(-5.)
      GO TO 360
  355 SD(I,K)=0.
      SKEW(I,K)=0.
  360 CONTINUE
C  . . . . . . OUTPUT FREQUENCY STATISTICS . . . . . . . . . . . . . . .
      TMP=SKEW(12,K)
      SKEW(13,K)=SKEW(1,K)
      GO TO(361,421),KIP
  361 WRITE(6,362)ISTA(K),(AV(I,K),I=1,12)
  362 FORMAT(/I6,8H    MEAN 12F8.3)
      WRITE(6,364)(SD(I,K),I=1,12)
  364 FORMAT(7X,7HSTD DEV 12F8.3)
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      WRITE(6,366)(SKEW(I,K),I=1,12)
  366 FORMAT(10X,4HSKEW 12F8.3)
      WRITE(6,368)(DO(I,K),I=1,12)
  368 FORMAT (8X6HINCRMT F7.2,11F8.2)
  421 CONTINUE
C • • • • • • TRANSFORM TO STANDARDIZED VARIATES • • • • • • • • • • • • • • •
  440 DO 490 K=1,NSTA
      M=1
      DO 480 J=1,NYRS
      DO 470 I=1,12
      M=M+1
      IF(Q(M,K).GT.TM) GO TO 470
      IZ=SD(I,K)+0.999
      IF(IZ.EQ.0) GO TO 460
      Q(M,K)=(Q(M,K)-AV(I,K))/SD(I,K)
C             PEARSON TYPE III TRANSFORM
      IZ=ABS(SKEW(I,K))+0.9999
      IF(IZ.EQ.0) GO TO 470
      TEMP=.5*SKEW(I,K)*Q(M,K)+1.
      TMP=1.
      IF(TEMP.GE.0.)GO TO 450
      TEMP=-TEMP
      TMP=-1.
  450 Q(M,K)=6.*(TMP*TEMP**(1./3.)-1.)/SKEW(I,K)+SKEW(I,K)/6.
      GO TO 470
  460 Q(M,K)=0.
  470 CONTINUE
  480 CONTINUE
  490 CONTINUE
C • • • • • • COMPUTE SUMS OF SQUARES AND CROSS PRODUCTS • • • • • • • • • • •
      DO 600 K=1,NSTA
      KX=K+1
      DO 510 L=KX,NSTAX
      DO 500 I=1,12
      RA(I,K,L) =(-4.)
      SUMA(I,L)=0.
      SUMB(I,L)=0.
      SQA(I,L)=0.
      SQB(I,L)=0.
      XPAB(I,L)=0.
  500 NCAB(I,L)=0
  510 CONTINUE
      DO 520 I=1,12
      DO 515 L=1,K
  515 NCAB(I,L)=-1
  520 RA(I,K,K)=1.
      M=1
      DO 550 J=1,NYRS
      DO 540 I=1,12
      M=M+1
      TEMP=Q(M,K)
      IF(TEMP.GT.TM) GO TO 540
      DO 530 L=KX,NSTAX
C             SUBSCRIPTS EXCEEDING NSTA RELATE TO PRECEDING MONTH
      LX=L-NSTA
      IF(LX.LT.1) TMP=Q(M,L)
      IF(LX.GT.0) TMP=Q(M-1,LX)
      IF(TMP.GT.TM)  GO TO 530
C             COUNT AND USE ONLY RECORDED PAIRS
      NCAB(I,L)=NCAB(I,L)+1
      SUMA(I,L)=SUMA(I,L)+TEMP
      SUMB(I,L)=SUMB(I,L)+TMP
      SQA(I,L)=SQA(I,L)+TEMP*TEMP
      SQB(I,L)=SQB(I,L)+TMP*TMP
      XPAB(I,L)=XPAB(I,L)+TEMP*TMP
  530 CONTINUE
  540 CONTINUE
  550 CONTINUE
C • • • • • • COMPUTE CORRELATION COEFFICIENTS • • • • • • • • • • • • • • •
      DO 598 I=1,12
      IF(IDGST.LE.0) GO TO 575
      WRITE(6,560)MO(I),ISTA(K)
  560 FORMAT(/39H RAW CORRELATION COEFFICIENTS FOR MONTHI3, 12H  AT STAT
     1IONI6)
      WRITE(6,570)(ISTA(L),L=1,NSTA)
  570 FORMAT(9H WITH STA I13,11I10)
  575 DO 580 L=KX,NSTAX
C             ELIMINATE PAIRS WITH LESS THAN 3 YRS DATA
      IF(NCAB(I,L).LE.2)GO TO 580
      TEMP=NCAB(I,L)
      AA(I,K,L)=SUMA(I,L)/TEMP
      AB(I,K,L)=SUMB(I,L)/TEMP
      TMP=(SQA(I,L)-SUMA(I,L)*SUMA(I,L)/TEMP)*(SQB(I,L)-SUMB(I,L)*SUMB
     1(I,L)/TEMP)
C             ELIMINATE PAIRS WITH ZERO VARIANCE PRODUCT
      IF(TMP.LE.0.)GO TO 580
      TMPB=1.
      TMPA=XPAB(I,L)-SUMA(I,L)*SUMB(I,L)/TEMP
C             RETAIN ALGEBRAIC SIGN
      IF(TMPA.LT.0.)TMPB=-TMPB
      TMPA=TMPA*TMPA/TMP
      TMPA=1.-(1.-TMPA)*(TEMP-1.)/(TEMP-2.)
      IF(TMPA.LT.0.)TMPA=0.
      RA(I,K,L)=TMPB*TMPA**.5
      IF(L.GT.NSTA) GO TO 580
      RA(I,L,K)=RA(I,K,L)
      AA(I,L,K)=AB(I,K,L)
      AB(I,L,K)=AA(I,K,L)
  580 CONTINUE
      IF(IDGST.LE.0) GO TO 596
      WRITE(6,590)(NCAB(I,L),RA(I,K,L),L=1,NSTA)
  590 FORMAT(12H  THIS MONTH 12(I4,F6.3))
      WRITE(6,595)(NCAB(I,L),RA(I,K,L),L=NSTAA,NSTAX)
  595 FORMAT(12H  LAST MONTH 12(I4,F6.3))
C             ELIMINATE NEGATIVE CORRELATIONS
  596 DO 597 L=1,NSTAX
      IZ=RA(I,K,L)
      IF(RA(I,K,L).LT.0..AND.IZ.NE.-4) RA(I,K,L)=0.
  597 CONTINUE
  598 CONTINUE
  600 CONTINUE
  612 TEMP=0.
      IF(IDGST.LE.0) GO TO 885
      WRITE(6,3)
C • • • • • • PRINT CORRELATION MATRIX • • • • • • • • • • • • • • • • • • • •
  815 DO 880 I=1,12
      WRITE(6,820)MO(I)
  820 FORMAT(//40H CONSISTENT CORRELATION MATRIX FOR MONTH I3)
      WRITE(6,825)(ISTA(K),K=1,NSTA)
  825 FORMAT(/3X,3HSTA 18I7)
      WRITE(6,830)
  830 FORMAT(20X,19H WITH CURRENT MONTH)
      DO 840 K=1,NSTA
  840 WRITE(6,850) ISTA(K),(RA(I,K,L),L=1,NSTA)
  850 FORMAT(I6,18F7.3)
      WRITE(6,860)
```

```
  860 FORMAT(20X38H WITH PRECEDING MONTH AT ABOVE STATION)
      ITP=NSTA+1
      DO 870 K=1,NSTA
  870 WRITE(6,850)ISTA(K),(RA(I,K,L),L=ITP,NSTAX)
  880 CONTINUE
  885 IF (IRCON.LE.0) GO TO 1015
      WRITE(6,3)
      M=1
      NVAR=NSTA+1
C              USE AVERAGE FOR MONTH PRECEDING RECORD
      DO 931 K=1,NSTA
  931 Q(1,K)=0.
      DO 990 J=1,NYRS
      DO 980 I=1,12
      M=M+1
      DO 970 K=1,NSTA
      QR(M,K)=BLANK
      IF(Q(M,K).LT.TM) GO TO 970
      NINDP=0
C              FORM CORRELATION MATRIX FOR EACH MISSING FLOW
      DO 950 L=1,NSTA
      LX=L+NSTA
      IF(L-K) 934,932,933
  932 NINDP=NINDP+1
      X(NINDP)=Q(M-1,L)
      AC(NINDP)=AB(I,K,LX)-AA(I,K,LX)
      R(L,NVAR)=RA(I,K,LX)
      GO TO 935
  933 IF(Q(M,L).GT.TM) GO TO 950
  934 NINDP=NINDP+1
      X(NINDP)=Q(M,L)
      AC(NINDP)=AB(I,K,L)-AA(I,K,L)
      R(NINDP,NVAR)=RA(I,K,L)
  935 ITP=NINDP
      R(ITP,ITP)=1.
      DO 940 LA=L,NSTA
      IF(LA.EQ.L) GO TO 940
      JX=LA+NSTA
      IF(L.EQ.K) GO TO 936
      IF(Q(M,LA).GT.TM.AND.LA.NE.K) GO TO 940
      ITP=ITP+1
      IF(LA.EQ.K)R(NINDP,ITP)=RA(I,L,JX)
      IF(LA.NE.K)R(NINDP,ITP)=RA(I,L,LA)
      GO TO 939
  936 IF(Q(M,LA).GT.TM) GO TO 940
      ITP=ITP+1
      R(NINDP,ITP)=RA(I,LA,LX)
C              ADD SYMMETRICAL ELEMENTS
  939 R(ITP,NINDP)=R(NINDP,ITP)
  940 CONTINUE
  950 CONTINUE
      ITMP=NINDP+1
      DO 952 L=1,NINDP
  952 R(L,ITMP)=R(L,NVAR)
C     ==========
      CALL CROUT(R,DTRMC,NINDP,8)
C     ==========
C              ADD RANDOM COMPONENT TO PRESERVE VARIANCE
      TEMP=RAN(IARG)
      TMP=RAN(IARG)
      TEMP=(-2.*ALOG(TEMP))**.5*SIN(6.2832*TMP)
C              COMPUTE FLOW
      IF (DTRMC.LE.1..AND.DTRMC.GE.0.) GO TO 955
      WRITE (6,7) I,K,DTRMC
      IF (DTRMC.GT.1.) DTRMC=1.
      IF (DTRMC.LT.0.) DTRMC=0.
  955 AL=(1.-DTRMC)**.5
      TEMP=TEMP*AL
      DO 960 L=1,NINDP
  960 TEMP=TEMP+B(L)*(X(L)-AC(L))
      Q(M,K)=TEMP
      QR(M,K)=E
  970 CONTINUE
  980 CONTINUE
  990 CONTINUE
      IF(KIP.EQ.2) GO TO 1994
      WRITE (6,993)
  993 FORMAT(33H RECORDED AND RECONSTITUTED FLOWS)
 1994 ANYRS=NYRS
      DO 1011 K=1,NSTA
      IF(KIP.EQ.2) GO TO 1995
      WRITE(6,995)(MO(I),I=1,12)
  995 FORMAT(/11H  STA  YEAR 12I8,6X,5HTOTAL )
 1995 M=1
      DO 998 J=1,NYRS
      ITP=0
      DO 997 I=1,12
      M=M+1
      TEMP=Q(M,K)
C              CONVERT STANDARD DEVIATES TO FLOWS
      TMP=SKEW(I,K)
      IF(TMP)2000,2001,2000
 2000 TEMP=((TMP*(TEMP-TMP/6.)/6.+1.)**3 -1.)*2./TMP
 2001 IF(QR(M,K).NE.E) GO TO 992
      IF(TEMP.GT.2..AND.SD(I,K).GT..3) TEMP=2.+(TEMP-2.)*.3/SD(I,K)
      TMP=(-2.)/SKEW(I,K)
      IF(SKEW(I,K)) 991,992,994
  991 IF(TEMP.GT.TMP) TEMP=TMP
      GO TO 992
  994 IF(TEMP.LT.TMP) TEMP=TMP
  992 TMP=TEMP*SD(I,K)+AV(I,K)
      Q(M,K)=10.**TMP-DQ(I,K)
      IF(Q(M,K).LT.0.) Q(M,K)=0.
      QM(I)=QR(M,K)
  996 IQ(I)=Q(M,K)+.5
  997 ITP=ITP+IQ(I)
      IYR=IYRA+J
      IF(KIP.EQ.2) GO TO 1000
      IF(IPCHQ.LE.0)GO TO 998
      WRITE (7,6) ISTA(K),IYR,(IQ(I),I=1,12)
  998 WRITE(6,999)ISTA(K),IYR,(IQ(I),QM(I),I=1,12) ,ITP
  999 FORMAT(1X,I4,I6,I8,A1,11(I7,A1),I10)
C  * * * * *RECOMPUTE MEAN AND STANDARD DEVIATION * * * * * * * * * * * * * *
 1000 DO 1001 I=1,12
      AV(I,K)=0.
 1001 SD(I,K)=0.
      M=1
      DO 1003 J=1,NYRS
      DO 1002 I=1,12
      M=M+1
      TEMP=ALOG(Q(M,K)+DQ(I,K))
      AV(I,K)=AV(I,K)+TEMP
 1002 SD(I,K)=SD(I,K)+TEMP*TEMP
 1003 CONTINUE
      DO 1004 I=1,12
      TEMP=AV(I,K)
```

```
      TMP=(SD(I,K)-TEMP*TEMP/ANYRS)/(ANYRS-1.)
      SD(I,K)=TMP**.5*.4342945
 1004 AV(I,K)=TEMP/ANYRS*.4342945
 1011 CONTINUE
C              PRINT ADJUSTED FREQUENCY STATISTICS
      IF(KIP.EQ.2) GO TO 1015
      WRITE(6,3)
      WRITE(6,1012)
 1012 FORMAT(/30H ADJUSTED FREQUENCY STATISTICS)
      DO 1013 K=1,NSTA
      WRITE (6,315) (MO(I),I=1,12)
      WRITE (6,362) ISTA(K),(AV(I,K),I=1,12)
      WRITE (6,364) (SD(I,K),I=1,12)
      WRITE (6,366) (SKEW(I,K),I=1,12)
      WRITE (6,368) (DO(I,K),I=1,12)
 1013 CONTINUE
C  * * * * * * FLOW GENERATION EQUATIONS * * * * * * * * * * * * * * * * * *
 1015 NINDP=NSTA
      NVAR=NSTA+1
      DO 1090 I=1,12
      IP=I-1
      IF (IP.LT.1) IP=12
      DO 1090 K=1,NSTA
      DO 1060 L=1,NSTA
C              CORRELATIONS IN CURRENT MONTH
      IF (L.GE.K) GO TO 1055
      R(L,NVAR)=RA(I,K,L)
      DO 1052 LA=L,NSTA
      LX=LA+NSTA
      IF (LA.LT.K) R(L,LA)=RA(I,L,LA)
      IF (LA.GE.K) R(L,LA)=RA(I,L,LX)
 1052 R(LA,L)=R(L,LA)
      GO TO 1060
C              CORRELATIONS WITH PRECEDING MONTH
 1055 LX=L+NSTA
      R(L,NVAR)=RA(I,K,LX)
      DO 1057 LA=L,NSTA
      R(L,LA)=RA(IP,L,LA)
 1057 R(LA,L)=R(L,LA)
 1060 CONTINUE
C     ==========
 1065 CALL CROUT(R,DTRMC,NINDP,8)
C     ==========
      DO 1070 L=1,NSTA
 1070 BETA(I,K,L)=R(L)
      IF(DTRMC.LE.1.) GO TO 1078
      WRITE(6,1072)I,K,DTRMC
 1072 FORMAT (34H INCONSISTENT CORREL MATRIX FOR I= I3,4H  K=I2,
     1 8H  DTRMC= F6.3)
      DTRMC=1.
 1078 IF(DTRMC.GE.0.) GO TO 1079
      WRITE(6,7)I,K,DTRMC
      DTRMC=0.
 1079 ALCFT(I,K)=(1.-DTRMC)**.5
 1080 CONTINUE
 1090 CONTINUE
C  * * * * * * GENERATE FLOWS  * * * * * * * * * * * * * * * * * * * * * * * *
 1091 JA=1
      N=0
      MA=0
 1095 DO 1100 K=1,NSTA
 1100 QPREV(K)=0.
C              GENERATE 2 YEARS FOR DISCARDING
      NJ=2
      JX=-2
      GO TO 5106
C              N = SEQUENCE NO., M = MONTH NO., JX = YEAR NO.
 1105 WRITE(6,3)
      N=N+1
      IF(KIP.EQ.2) GO TO 5106
      WRITE (6,1106) N
 1106 FORMAT (27H GENERATED FLOWS FOR PERIOD I3)
 5106 JXTMP=JX
      DO 3107 K=1,NSTA
      DO 3106 I=1,12
      NLG(I,K)=0
      AVG(I,K)=0.
      SDV(I,K)=0.
 3106 CONTINUE
 3107 CONTINUE
 1108 DO 3125 J=JA,NJ
      M=12*(J-1)+1
      JX=JX+1
      DO 1125 I=1,12
      M=M+1
      DO 1120 K=1,NSTA
C              RANDOM COMPONENT
 1111 TEMP=RAN(IARG)
      TMP=RAN(IARG)
      TEMP=(-2.*ALOG(TEMP))**.5*SIN(6.2832*TMP)
      TEMP=TEMP*ALCFT(I,K)
C              GENERATE CORRELATED STANDARD DEVIATE
      DO 1110 L=1,NSTA
      TMP=QPREV(L)
      IF(L.LT.K)TMP=Q(M,L)
 1110 TEMP=TEMP+BETA(I,K,L)*TMP
      NLG(I,K)=NLG(I,K)+1
      AVG(I,K)=AVG(I,K)+TEMP
      SDV(I,K)=SDV(I,K)+TEMP*TEMP
      Q(M,K)=TEMP
      QPREV(K)=TEMP
 1120 CONTINUE
 1125 CONTINUE
 3125 CONTINUE
      DO 1130 K=1,NSTA
 1122 IF(NJ+JXTMP.GT.0.AND.KIP.EQ.1) WRITE(6,995) (MO(I),I=1,12)
      DO 3126 I=1,12
      TEMP=NLG(I,K)
      AVG(I,K)=AVG(I,K)/TEMP
      SDV(I,K)=((SDV(I,K)-AVG(I,K)**2*TEMP)/TEMP)**.5
      IF(NLG(I,K).GT.19.AND.KIP.EQ.1) WRITE(6,5126) ISTA(K),MO(I),AVG(I,
     1K),SDV(I,K)
 3126 CONTINUE
 5126 FORMAT (4H STAI4,8H   MONTHI3,7H   MEANF6.3,10H   STD DEVF5.3)
      JX=JXTMP
      DO 3129 J=JA,NJ
      JX=JX+1
      M=12*J-11
      IF (JX.LE.0) GO TO 3129
      ITP=0
      DO 1129 I=1,12
      M=M+1
C              TRANSFORM TO LOG PEARSON TYPE III VARIATE (FLOW)
      TMP=SKEW(I,K)
      IZ=ABS(SKEW(I,K))+0.9999
      IF(IZ.EQ.0) GO TO 1126
```

```
      IF (NLG(I,K).GT.19) Q(M,K)=(Q(M,K)-AVG(I,K))/SDV(I,K)
      TMP=((TMP*(Q(M,K)-TMP/6.)/6.+1.)**3 -1.)*2./TMP
      TEMP=(-2.)/SKEW(I,K)
      IF(SKEW(I,K)) 1123,1126,1124
 1123 IF(TMP.GT.TEMP)TMP=TEMP
      GO TO 1127
 1124 IF(TMP.LT.TEMP) TMP=TEMP
      GO TO 1127
 1126 TMP=Q(M,K)
 1127 IF(TMP.GT.2..AND.SD(I,K).GT..3) TMP=2.+(TMP-2.)*.3/SD(I,K)
      TMP=TMP*SD(I,K)+AV(I,K)
      Q(M,K)=10.**TMP-DQ(I,K)
 3128 IF(Q(M,K).LT.0.) Q(M,K)=0.
 1128 IQ(I)=Q(M,K)+.5
      ITP=ITP+IQ(I)
 1129 CONTINUE
      IQ(13)=ITP
      IF(KIP.EQ.2) GO TO 3129
      WRITE (6,11) ISTA(K),JX,(IQ(I),I=1,13)
      IF(IPCHQ.LE.0)GO TO 3129
      WRITE (7,6) ISTA(K),JX,(IQ(I),I=1,12)
 3129 CONTINUE
 1130 CONTINUE
 1250 NJ = NYMXG
C              GO TO NEW JOB
 1270 IF(NYRG.LE.0) GO TO 1271
      IF(NJ.GT.NYRG)NJ=NYRG
      NYRG=NYRG-NJ
      GO TO 1105
 1271 RETURN
      END


      SUBROUTINE CROUT(RX,DTRMC,NINDP,B)
      DIMENSION B(20),R(10,11),RX(10,11)
      DOUBLE PRECISION R,B,RX
      NVAR=NINDP+1
      DO 5 J=1,NINDP
      DO 4 K=1,NVAR
    4 R(J,K)=RX(J,K)
    5 CONTINUE
      IF(NINDP.GT.1)GO TO 10
      B(1)=R(1,2)/R(1,1)
      DTRMC=B(1)*B(1)
      RETURN
C  * * * * * * DERIVED MATRIX  * * * * * * * * * * * * * * * * * * * * * * * * *
   10 DO 20 K=2,NVAR
   20 R(1,K)=R(1,K)/R(1,1)
      DO 60 K=2,NINDP
      ITP=K-1
      DO 40 J=K,NINDP
      DO 30 I=1,ITP
      L=K-I
   30 R(J,K)=R(J,K)-R(J,L)*R(L,K)
      IF(J.EQ.K) GO TO 40
      R(K,J)=R(J,K)/R(K,K)
   40 CONTINUE
      DO 50 I=1,ITP
      L=K-I
   50 R(K,NVAR)=R(K,NVAR)-R(L,NVAR)*R(K,L)
   60 R(K,NVAR)=R(K,NVAR)/R(K,K)
C  * * * * * * BACK SOLUTION * * * * * * * * * * * * * * * * * * * * * * * * *
      B(NINDP)=R(NINDP,NVAR)
      DO 80 I=2,NINDP
      J=NVAR-I
      IX=I-1
      B(J)=R(J,NVAR)
      DO 70 L=1,IX
      K=J+L
   70 B(J)=B(J)-B(K)*R(J,K)
   80 CONTINUE
      DTRMC=0.
      DO 90 J=1,NINDP
   90 DTRMC=DTRMC+B(J)*RX(J,NVAR)
      RETURN
      END
```

Suggestions for More Efficient Use of the Operating Rule Program

The user may be somewhat bewildered as to the proper formulation of certain input parameters to achieve the desired objectives. Therefore a few suggestions are made for getting started on a computation.

The projected water demand is satisfied by two components: (1) the natural yield of the system, and (2) the supplement from the desalting plant. The natural yield of the system is determined by the program and is not known beforehand. This makes selection of the trial plant size somewhat difficult. If the plant size selected is too small, then even the high yield producing rules fall short of the required demand. On the other hand, if the plant selected is too large, the lower yield producing rules exceed the target demand. In either case, the set of feasible rules cannot be determined and the computer time involved is wasted. Experience with the program has shown that a plant size 1.30 times the required increase in firm yield is usually near optimal.

To decrease the wasted computer time, a pilot run should be made utilizing the best information available about the physical system under study and with the trial plant size suggested above. Select one or two operating rules and make a run using two or three periods. If one high and one low yield producing rule are used, the results will indicate an upper and lower limit on the firm yield for the given plant size. Actually, the information gained is twofold. First, the ability of the selected plant to produce the required yield can be judged, and second, if the plant is adequate, information is gained for formulating the operating rules. If the required demand is in the range of the high yield producing rules, then the lower yield producing rules need not be considered, and vice versa. By judicious selection of the operating rules, the computational effort can be greatly reduced.

APPENDIX B

EVALUATION OF THE ADEQUACY OF STREAMFLOW OPERATIONAL HYDROLOGY IN DUPLICATING EXTENDED PERIODS OF HIGH AND LOW FLOWS

by
Roland W. Jeppson and Calvin G. Clyde

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EVALUATION OF THE ADEQUACY OF STREAMFLOW OPERATIONAL HYDROLOGY IN DUPLICATING EXTENDED PERIODS OF HIGH AND LOW FLOWS

Introduction

In recent years the generation of synthetic hydrologic records, particularly streamflow data, has been common in hydrologic studies which use a simulation approach. *Operational hydrology* is the term used to denote the generation of synthetic data. One of the most active groups promoting simulation techniques and operational hydrology was founded by Professor Harold A. Thomas, Jr. at Harvard, and from this group a number of publications originated (see Hufschmidt and Fiering, 1966; and Fiering, 1967). The operational hydrology computer program by the U.S. Corps of Engineers (Beard, 1965, and Hydrologic Engineering Center, 1967) has been used in research at USU supported by the Office of Saline Water, U.S. Dept. of the Interior.

Much thought and many analyses have contributed to present techniques of operational hydrology. It has long been recognized that monthly and seasonal flows demonstrate a high order of persistence, reflected by large correlation coefficients between flows in successive time periods. Although this is true to a lesser extent for annual values, examination of many flow records using spectral density methods, correlograms and other techniques discloses cycles that range over periods of several years. The fact that a long period of low or high flow can sometimes be extremely long has been called by Mandelbrot and Wallis (1968) the "Joseph Effect." Some have questioned the significance of these results, but analysis of precipitation records has demonstrated that it is possible to create such cyclic effects by a purely random variable as shown by Crippen (1965). Just the same persistently high flow and drought sequences are present in some historic streamflow data. Furthermore, the watershed can accentuate precipitation cycles so that the streamflow cycles become even more extreme. There might well be some as yet unknown meteorologic cause for such extended cycles. Several hypotheses have been suggested including the influence of solar spots, cosmic dust, and radiation belts. Whatever the cause, natural streamflow in certain regions exhibits a persistence even on an annual event basis that is difficult to attribute to a random variable, and evidently is also difficult to duplicate with operational hydrology.

While considerable disappointment with specific hydrologic models has been expressed by hydrologists (see Yevdjevich, 1968), verbal communication with Warren Hall at the University of California at Riverside, and Leo R. Beard and Harold Kubic of the Hydrologic Engineering Center at Sacramento, indicated that operational hydrology programs adequately retain critically low and high sequences for streams in more humid regions, but fail to adequately duplicate the "Joseph Effect" for streams in arid regions. These comments lead to careful examination of the generated streamflow obtained from the operational hydrology computer program. It is clear that such an evaluation is needed because the approach used in the OSW sponsored study for evaluating the incremental increases in safe yield obtainable from standby desalted water sources depends directly upon the simulated streamflow data for its results. The study of the adequacy of the generated streamflow data has not been exhaustive. Rather, a computer program applicable to any stream has been developed to aid in evaluating the adequacy of the generated streamflow. (The input data called for by this program is described in a latter section along with a listing of the FORTRAN source statements.) Other methods than those used in the program might well have been selected for this evaluation. The urgency of examining the generated streamflow before proceeding further into the major work of the OSW contract necessitated that the evaluation be made without delay. Because the computer program thusly developed might be of aid to others in evaluating operational hydrologies, it seemed desirable to document the approach used and to list and explain the computer program in a separate report specifically directed to the evaluation of generated streamflow data.

Method of Approach

A preliminary analysis comparing the monthly means, monthly standard deviations, annual means and annual standard deviations of generated data and historic data from several streams indicated that these statistical parameters of the generated data were close to the same historic parameters. In essence this comparison simply verified the proper operation of the operational hydrology program, since these parameters are maintained in the generation process.

The deficiency in generated streamflow data, as others have pointed out, is that in consecutive annual events the historic data tend to be either consistently higher or lower than the generated data for some streams. To examine this characteristic of the generated streamflow data all possible running averages (averages of consecutive monthly flows) within the streamflow record are computed for several different lengths of periods. The computer program, developed to accomplish this computation, has been designed to permit the analyses of the running average data for several specified periods of consecutive months during the same execution of the program. For the analyses already performed at USU, periods starting with 24 consecutive months and going through 192 consecutive months in increments of 24 months have been used. The computed running averages represent an additional data set covering flows of extended periods of time. The number of individual running averages computed in this manner are given by,

$$N_r = 12\,N_y - K + 1 \qquad \ldots (1)$$

in which N_y is the number of years of streamflow data, and K is the length of the period of consecutive months. While these individual averages are not independent, a frequency distribution of the resulting data indicates persistency trends of the data. To obtain this frequency distribution running averages are ranked in order of magnitude by the program from high to low. In addition, the mean, variance, standard deviation and skewness coefficient of the running averages of each period are computed, so that one might obtain the frequency distribution under the assumption that the data fit a normal distribution. The ranked running averages are then plotted as the ordinate against the probability computed by

$$p = \frac{n}{N_r + 1} \qquad \ldots\ldots\ldots (2)$$

as the abscissa. In Eq. 2 n refers to the rank number.

By comparing the distribution of running averages obtained from the historic data with those resulting from the data obtained from the operational hydrology program it is possible to determine whether extended periods of droughts and high flows are duplicated. If the running averages associated with small probabilities (i.e. the high flows) obtained from the generated streamflow data are smaller than the corresponding averages from the historic data, then the generated data does not maintain the needed dependence between annual events. Likewise if the running averages associated with large probabilities (i.e. the low flows) from the generated data are not as small as those from the historic data, persistence of droughts are not duplicated. In fact since the generated data cover a much longer time period than the historic data, its record should actually contain both larger and smaller running averages than the historic data.

An index to how well the generated data maintains critical periods is the difference between generated and historic standard deviations of the running averages. Since the standard deviation is a measure of the spread about the mean, the standard deviations of the running averages from the generated data should not be consistently smaller than those resulting from the historic data. The computer program contains instructions which compare the two standard deviations for each specified period of consecutive months by printing the difference between the two values. In addition the mean and standard deviation of these differences among the specified periods of consecutive months is computed and a value of t computed by

$$t = \frac{X_d\, N_p}{\sigma_p} \qquad \ldots\ldots\ldots (3)$$

in which X_d is the average difference between the two standard deviations, N_p is the number of separate periods used in the analyses and σ_p is the standard deviation of this same difference. While the value of t computed by Eq. 3 does not represent a true distribution of difference in mean values, an idea of the likelihood that the generated data is from the same population as the historic data can be acquired by comparing its value with the tabulated t-distribution.

Results from Analyses of Three Streams

The streamflow at each gaging station is influenced by unique and complex interrelated phenomena. These phenomena are the result of the meteorology, geology and hydrology of that particular area. Completely meaningful generalizations cannot be made about watershed types, areal location, or climate and their effects on streamflow. Often adjacent watersheds with similar topographical characteristics may have streamflows differing considerably both in total magnitude and seasonal distribution. It is necessary, therefore, to analyze streamflow data for each watershed separately to ascertain the adequacy of a particular operational hydrology for that stream gaging site. Three separate stream gaging sites have been selected for analysis of their streamflow in this report.

These three sites are all in different parts of the United States and their geologic histories are quite different. The first site, Cottonwood Creek near Orangeville, Utah, is in the Colorado River Basin in Central Utah, a relatively arid part of the United States. A significant portion of the streamflow results from groundwater storage, because flow continues through periods of neither snowmelt nor rainfall. The second selection is at the Cachuma project site in California. The streamflow at this site varies drastically when contrasted with Cottonwood Creek, and within a period of a month a difference of several thousand cubic feet per second of flow are commonly observed. Even though this area is not as arid as the Cottonwood Creek region, zero flow has occurred for many separate periods several months in length. The third selection is on the East Coast of the United States, Schoharie Creek at Prattsville, New York, a stream in a region of higher annual precipitation and exhibiting less erratic flow fluctuations than the Cachuma data.

The selection of these three stream gaging sites was not based on an attempt to find streams with peculiar behavior. Rather their selection resulted because they represent differing conditions and the latter two are to be used as bench marks on which the operating rule program resulting from the OSW contract is to be tested. The selection of Cottonwood Creek resulted because of the availability of good streamflow records and because it lies in a region similar to those in which other investigators have noted that operational hydrology programs do not adequately reproduce the "Joseph Effect" in historic data.

Partial results from the analyses provided by the computer program are given below for each of the three selected sites. These results are presented not only to document the findings regarding the adequacy or inadequacy of the operational hydrology program for each stream but also to illustrate how judgment might be used in interpreting the results from similar analyses of other streams. For each of these streams 500 years of data were obtained from the operational hydrology program using the available historic data as input. For each stream the generated data were obtained as 10 groups of 50 years each.

Cottonwood Creek near Orangeville, Utah

Historic streamflow data are available for Cottonwood Creek near Orangeville, Utah, from 1910 through 1965. The watershed area contributing to the flow at the gaging station is 205 square miles. For the entire 56 year period of record the streamflow data represents the natural flow of the stream with the exception of small diversions for irrigation above the gaging station, which are not measured. Diversions from the headwaters of Cottonwood Creek through Ephraim and Spring City tunnels, constructed by the Bureau of Reclamation in 1936 and 1938 respectively to the San-Pitch River Basin within the Great Basin, have been added to the measured flow at the station site near Orangeville, in order for the historic data to represent natural conditions.

For both the historic and the generated streamflow data, the cumulative frequency distributions of periods starting with all possible averages from 24 consecutive months through 192 consecutive months in increments of 24 months were obtained. On Fig. 1 are graphs on which the results of the frequency analyses are displayed. In comparing the curves on the graphs resulting from the generated data with those from the historic data a smoothing effect can be detected. A certain amount of this effect would be expected because the sample of data from the generated streamflow is larger. One might also note that the flows which are exceeded for small probabilities of occurrence (high flows), particularly for the longer periods of consecutive months as given by the analysis of the historic data, are larger than the corresponding flows as given by the analysis of the generated data. Furthermore, for larger probabilities of occurrence the average flow rates resulting from the analyses of the generated data are larger. Table 1 has been prepared to illustrate these differences.

If the generated data maintained the "Joseph Effect" which the historic data exhibits, this difference should not have occurred. In fact because of the larger number of generated data, one might expect the opposite tendency.

A further indication of the inadequacy of the generated data in duplicating extended critical periods is given in Table 2 in which the standard deviations of the running averages from both the historic and generated data are given. The fact that, for all periods of consecutive months, the standard deviations from the historic data are larger than those from the generated data indicates that the generated data do not contain as many persistently high-flow or drought sequences as do the historic data.

The conclusion, therefore, is that the operational hydrology program does not adequately reproduce the "Joseph Effect" for Cottonwood Creek near Orangeville.

Table 1. Average flowrate (ac-ft/month) over the given period of consecutive months that will be exceeded for several probabilities of occurrence. The flowrates are for both the historic and generated streamflow of Cottonwood Creek near Orangeville, Utah.

Period (Consecutive Months)	Probability of occurrence							
	2%		10%		90%		98%	
	Historic	Generated	Historic	Generated	Historic	Generated	Historic	Generated
24	9786	10,010	9210	8400	4068	4170	2797	3480
48	8769	8,960	8119	7670	4533	4660	3663	4110
72	8220	8,550	7930	7450	4838	4900	3557	4370
96	8095	7,930	7680	7320	5058	5180	4760	4510
120	8115	7,810	7564	7200	5060	5280	4719	4710
144	8164	7,550	7467	7080	5226	5370	4768	4890
168	7878	7,370	7122	6960	5365	5430	5165	5090
192	7437	7,200	7097	6900	5416	5490	5182	5170

Table 2. Comparison of standard deviations of running average data of streamflow at Cottonwood Creek near Orangeville, Utah. (Units are in ac-ft/month.)

No. of Consecutive Months	Standard deviations			
	Historic	Generated	Difference	Percent Difference
24	1810	1680	+ 130	7.25
48	1350	1180	+ 170	12.71
72	1090	970	+ 120	11.15
96	934	835	+ 99	11.47
120	895	728	+ 167	18.70
144	822	641	+ 181	23.30
168	695	570	+ 125	17.96
192	590	517	+ 73	12.25

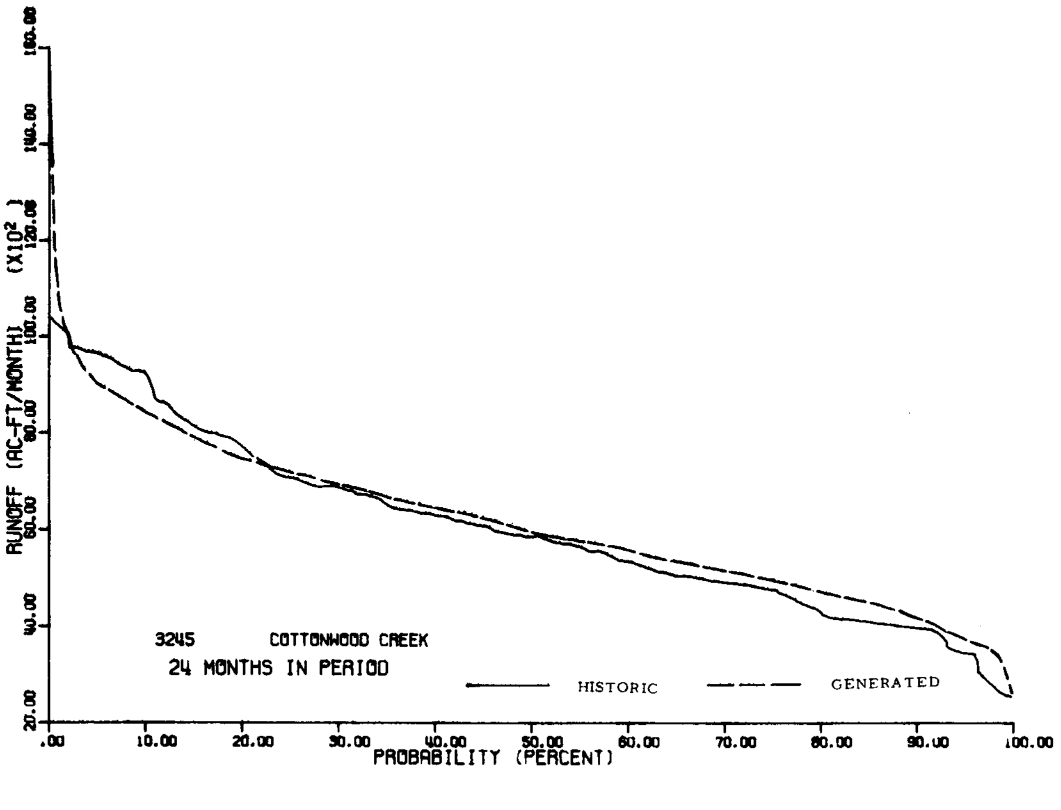
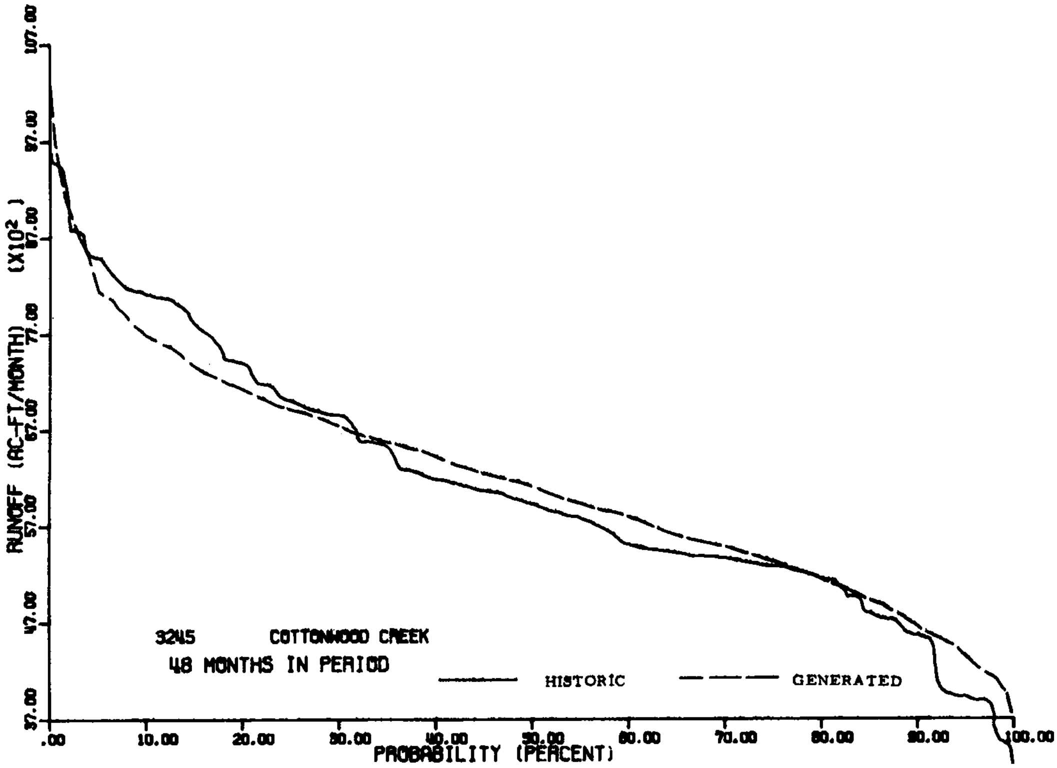
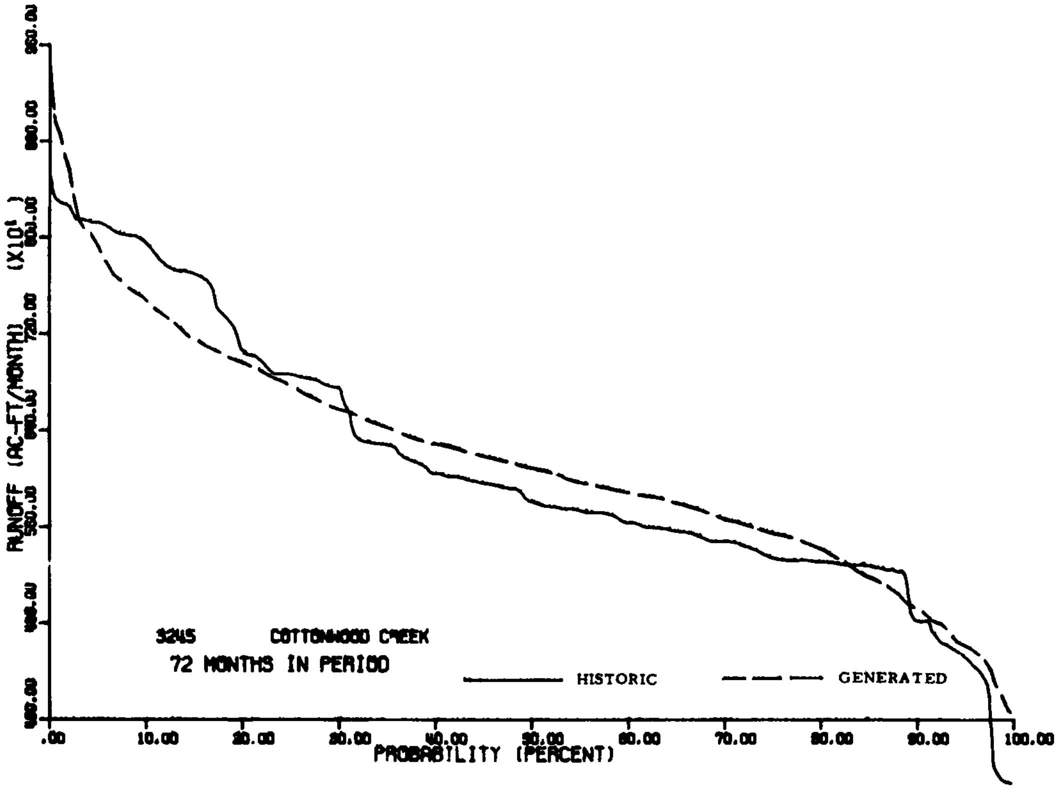


Figure 1. Relationships between average quantities of runoff over extended periods of time and probability of occurrence for Cottonwood Creek near Orangeville, Utah.





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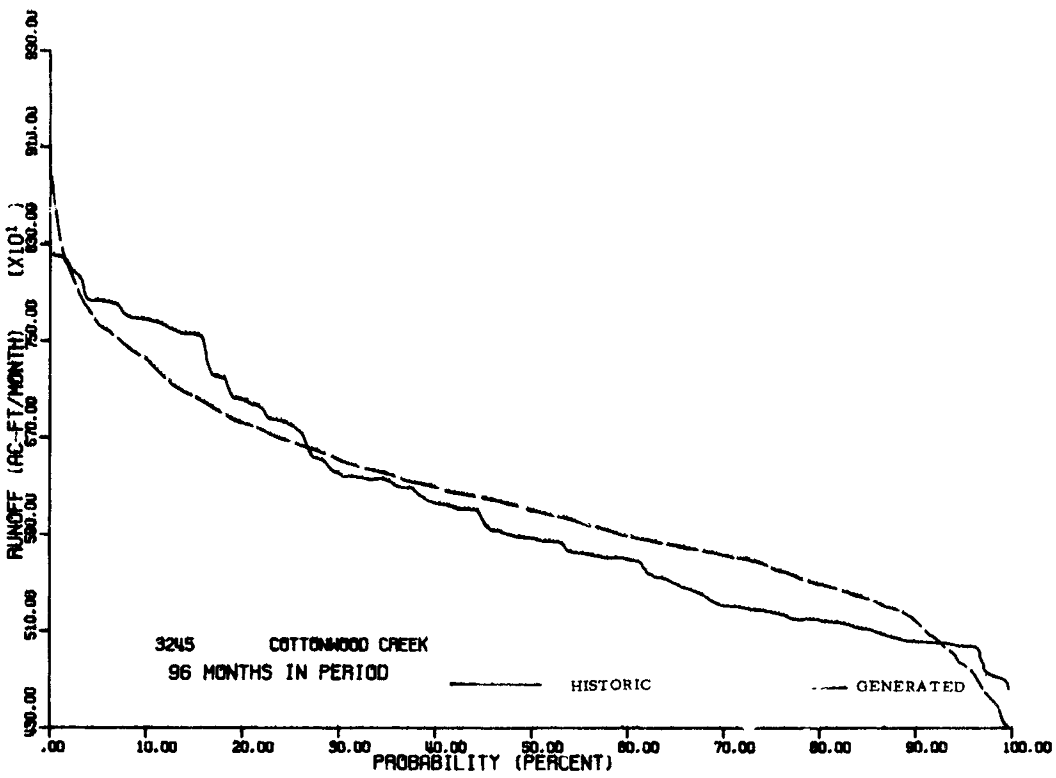


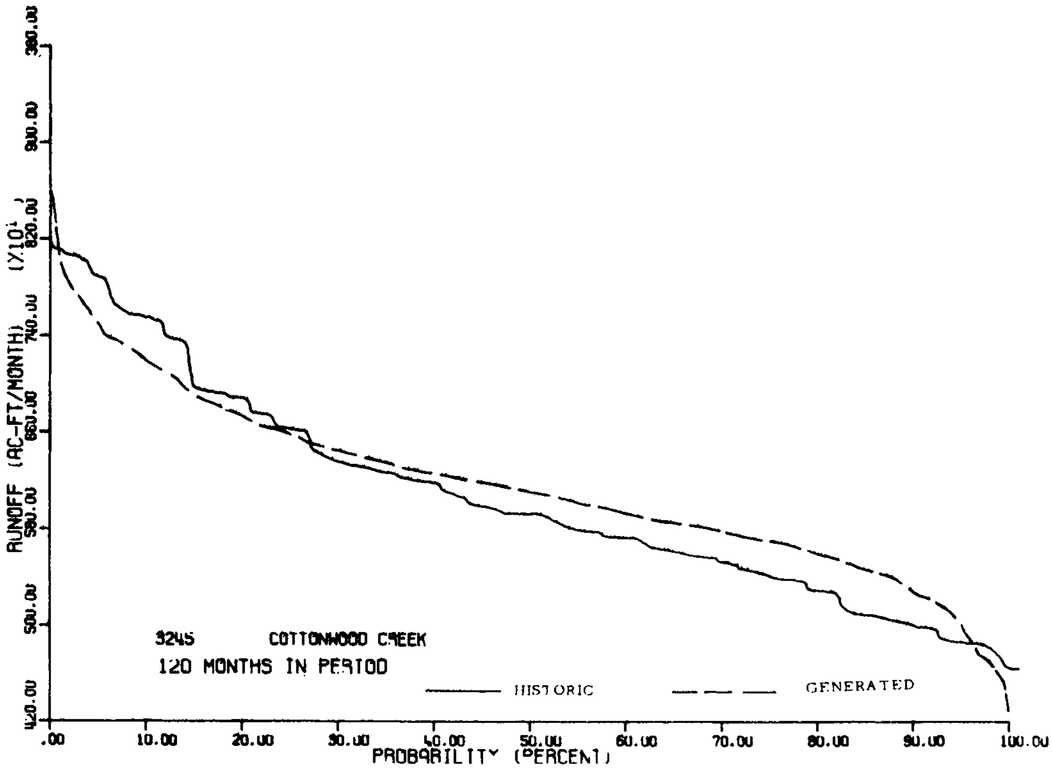
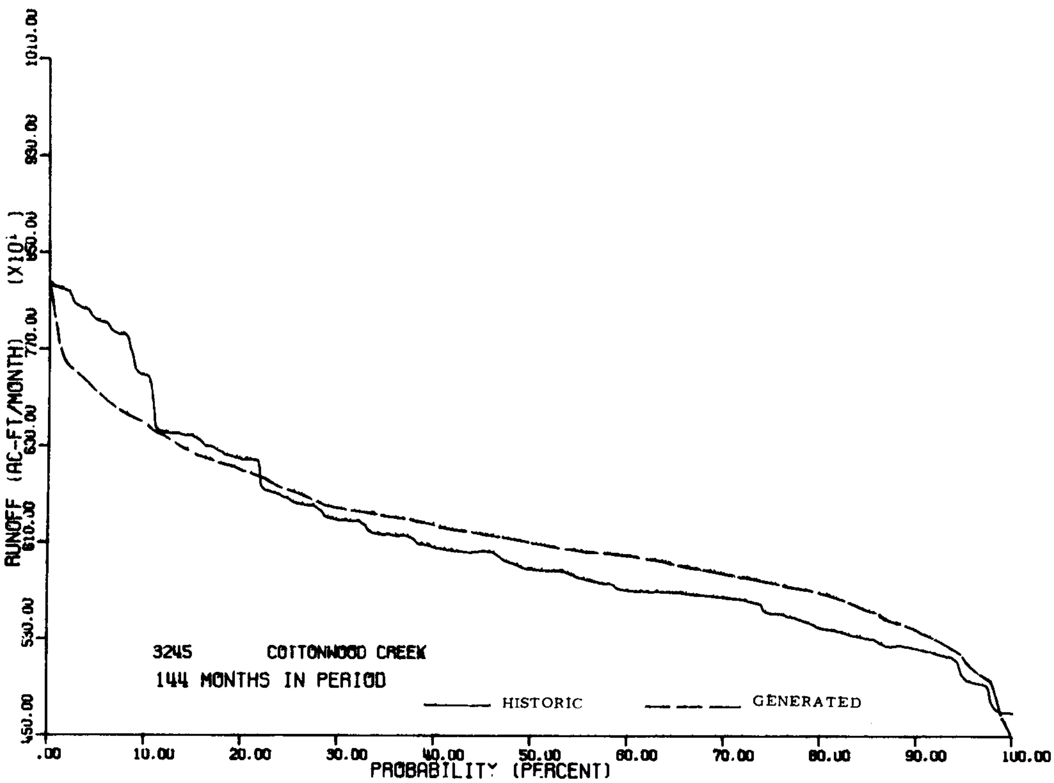


Figure 1. Continued.



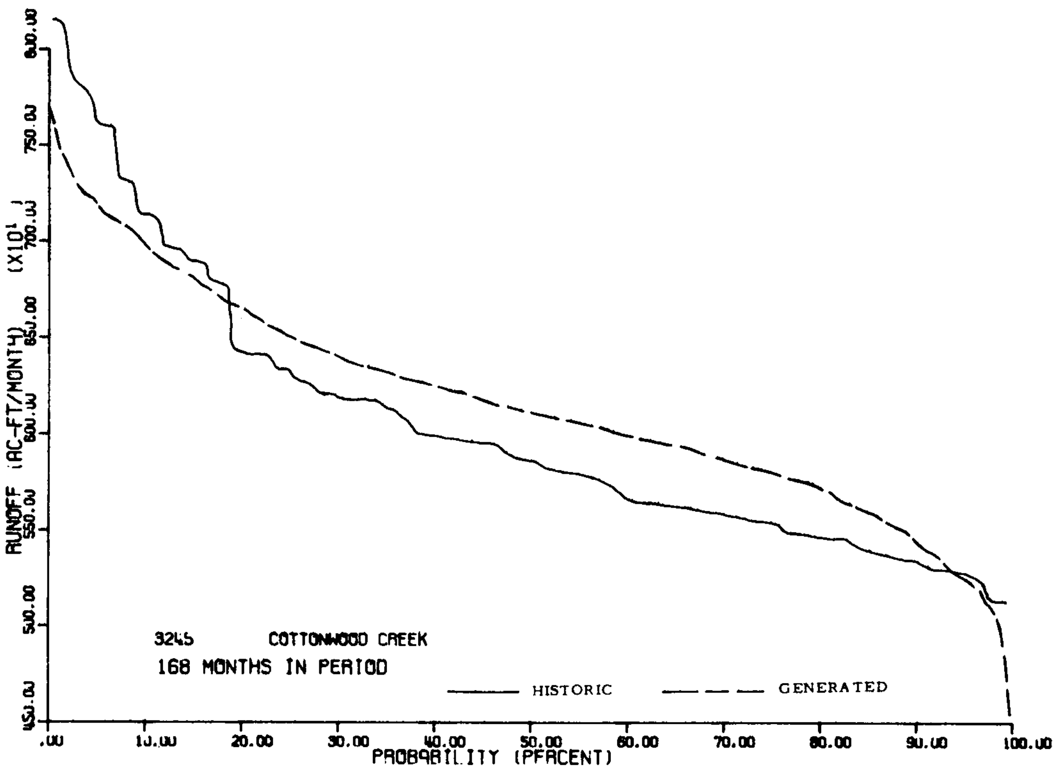


Figure 1. Continued.

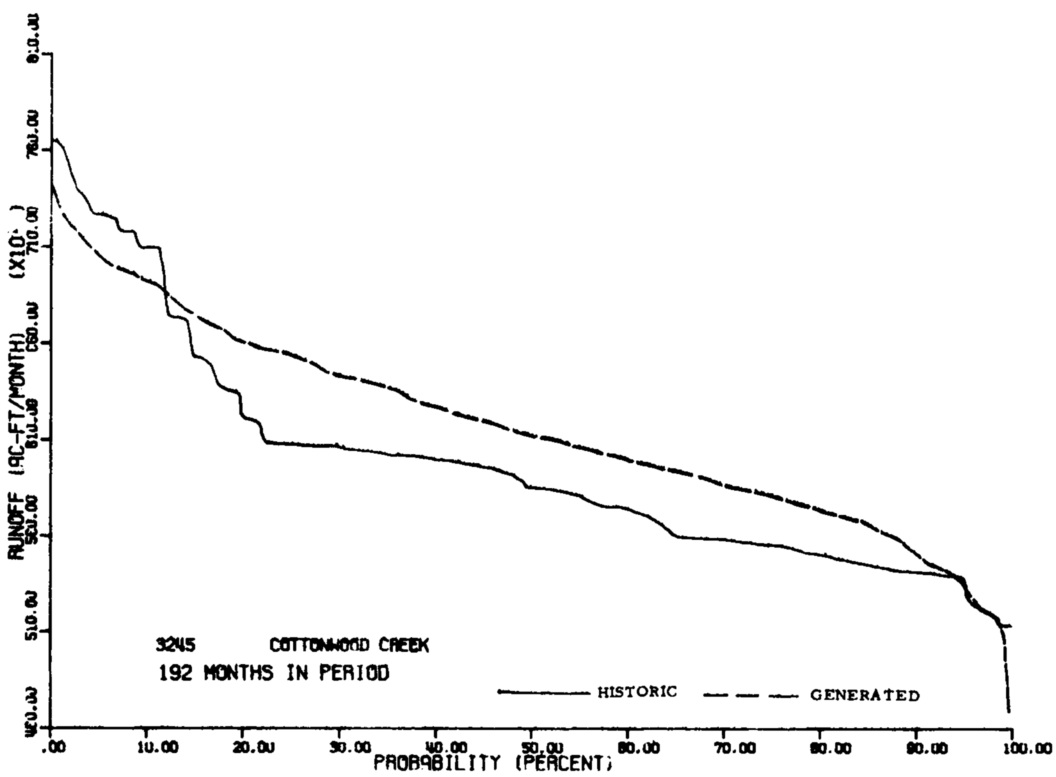


Figure 1. Concluded.

Streamflow at the Cachuma Project, California

Historic streamflow data for the period 1905 through 1962 were obtained from the California Division of Water Resources. After inputing these historic data to the operational hydrology program and generating 500 years of streamflow data in 10 groups of 50 years, both the historic and generated data were used as input to the program described in this report. Each of the curves on Fig. 2 displays the results of the frequency analyses of the running averages over the specified period of consecutive months. Table 3 summarizes the runoff quantities associated with four probabilities of occurrence. The results from the frequency analyses show that the generated streamflow for extended periods of droughts are slightly higher than the corresponding historic averages. This effect is less pronounced than for Cottonwood Creek near Orangeville. Just the same the results seem to indicate that the generated data are not adequately reproducing droughts. On the other hand the averages from the generated data are greater than the historic data for high flows or low probabilities. Extended periods of high flow are therefore retained in the operational hydrology program for the flows at Cachuma.

Table 3. Average flowrate (ac-ft/month) over the given period of consecutive months that will be exceeded for four probabilities of occurrence. The flowrates are for both the historic and generated streamflow at the Cachuma Project, California.

Period (Consecutive Months)	Probability of occurrence							
	2%		10%		90%		98%	
	Historic	Generated	Historic	Generated	Historic	Generated	Historic	Generated
24	2600	3500	1935	1810	16	81	6.7	26
48	2290	2750	1550	1600	130	182	14.5	84
72	2100	2290	1320	1330	195	258	110	140
96	1880	1900	1245	1297	188	300	149	184
120	1710	1770	1080	1243	213	337	196	240
144	1585	1590	1060	1175	222	369	197	270
168	1465	1450	1055	1117	241	413	198	285
192	1300	1365	960	1130	295	445	220	290

Table 4 shows a comparison of the standard deviations. The differences in the standard deviations have both negative and positive values. Because the magnitudes of these differences are relatively large, it cannot be concluded that the operational hydrology program adequately reproduces extended trends of the historic record. Conversely, it cannot be concluded that the operational hydrology program is not reproducing the "Joseph Effect."

Table 4. Comparison of standard deviations of running average data of streamflow at Cachuma, California. (Units are in ac-ft/month)

No. of Consecutive Months	Standard deviations			
	Historic	Generated	Difference	Percent Difference
24	7220	9280	-2040	-28.3
48	5920	6250	- 320	- 5.4
72	5180	4850	+ 330	+ 6.37
96	4600	4080	+ 520	+12.70
144	3650	3190	+ 460	+12.60
168	3140	2900	+ 240	+ 7.64

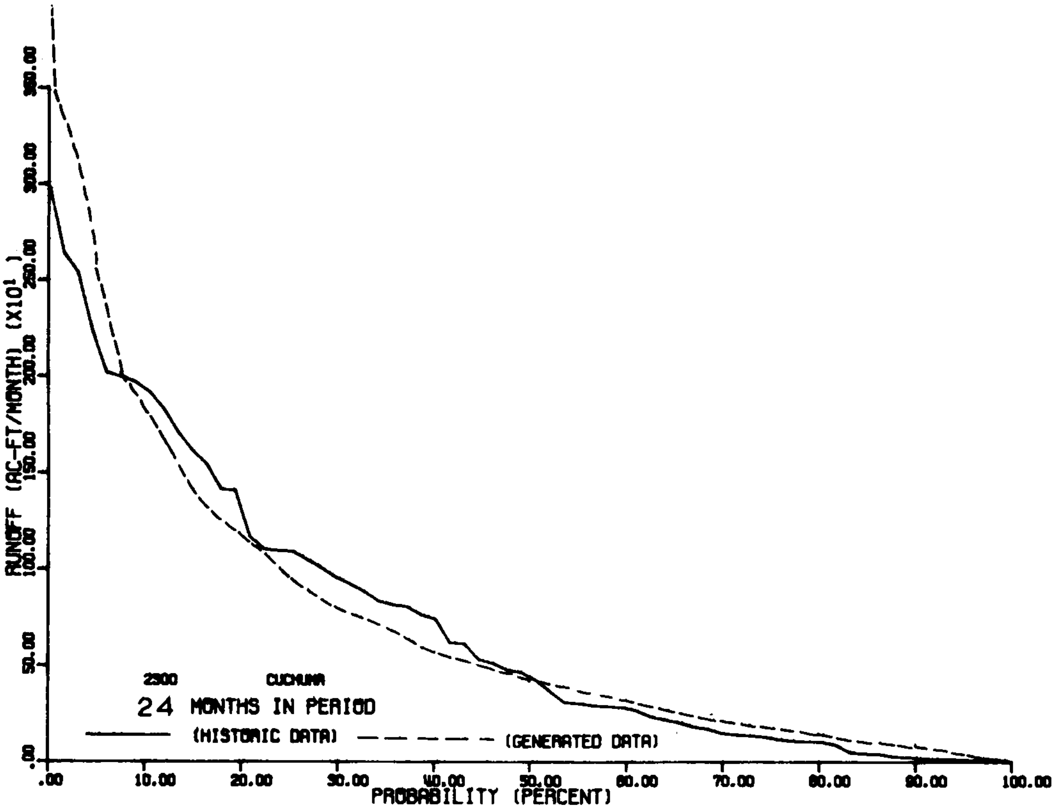
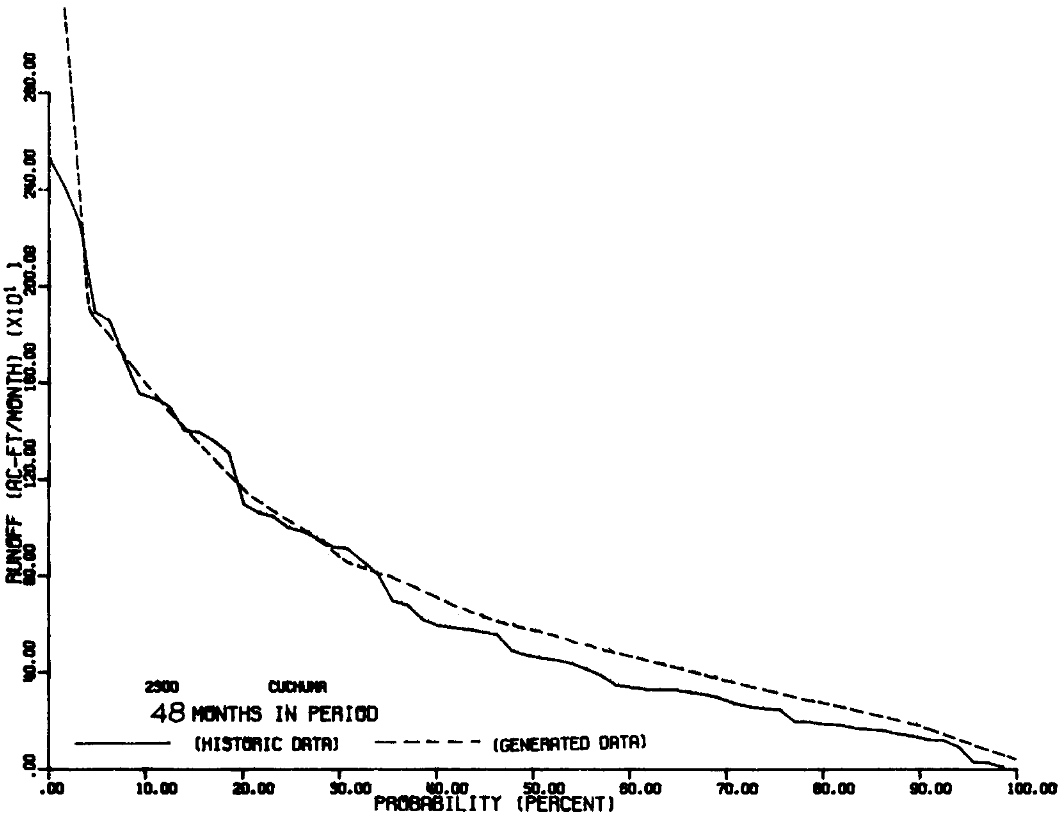
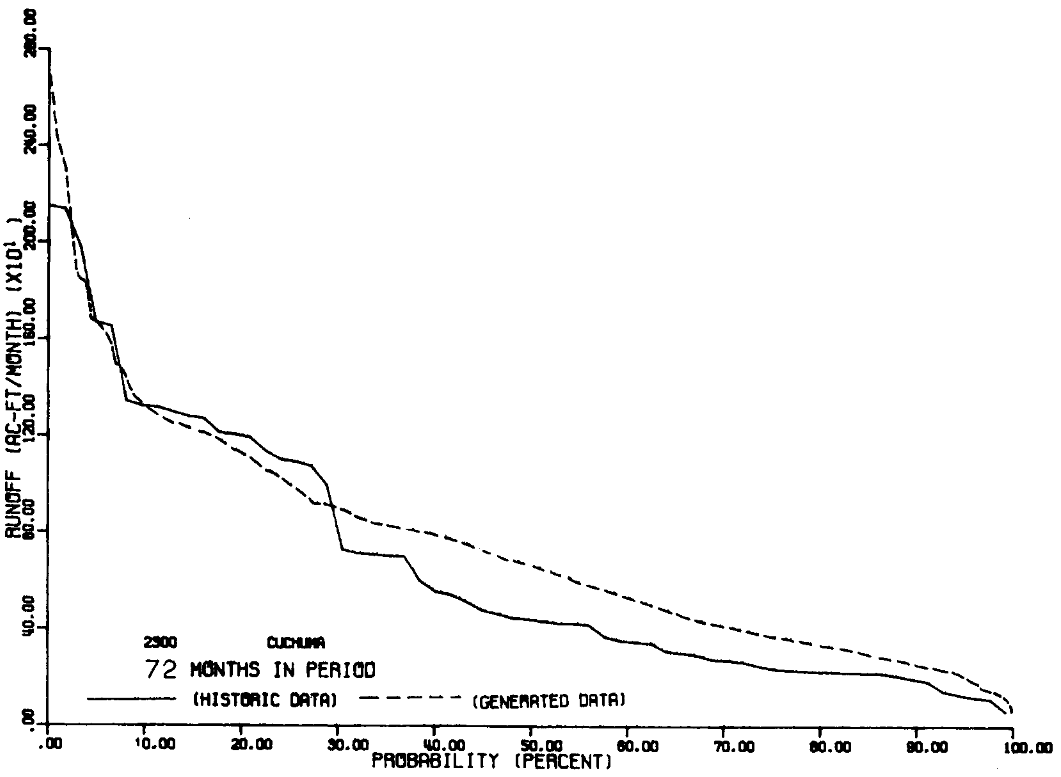


Figure 2. Relationships between average quantities of runoff over extended periods of time and probability of occurrence for streamflow at the Cachuma Project, California.





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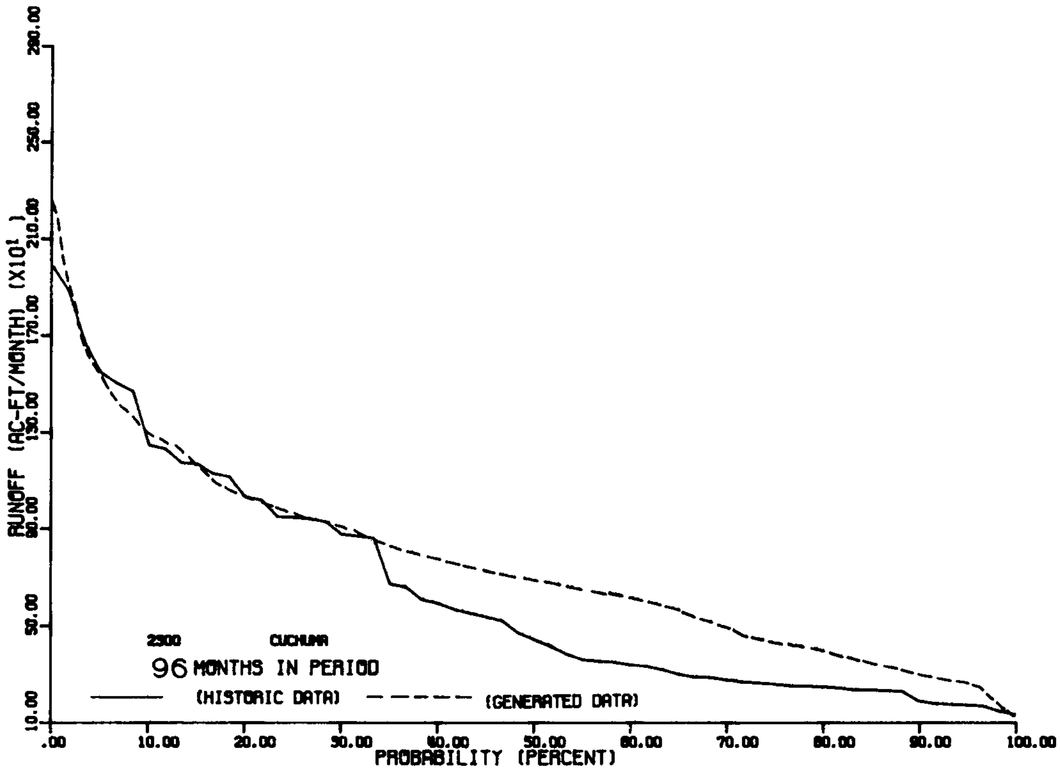

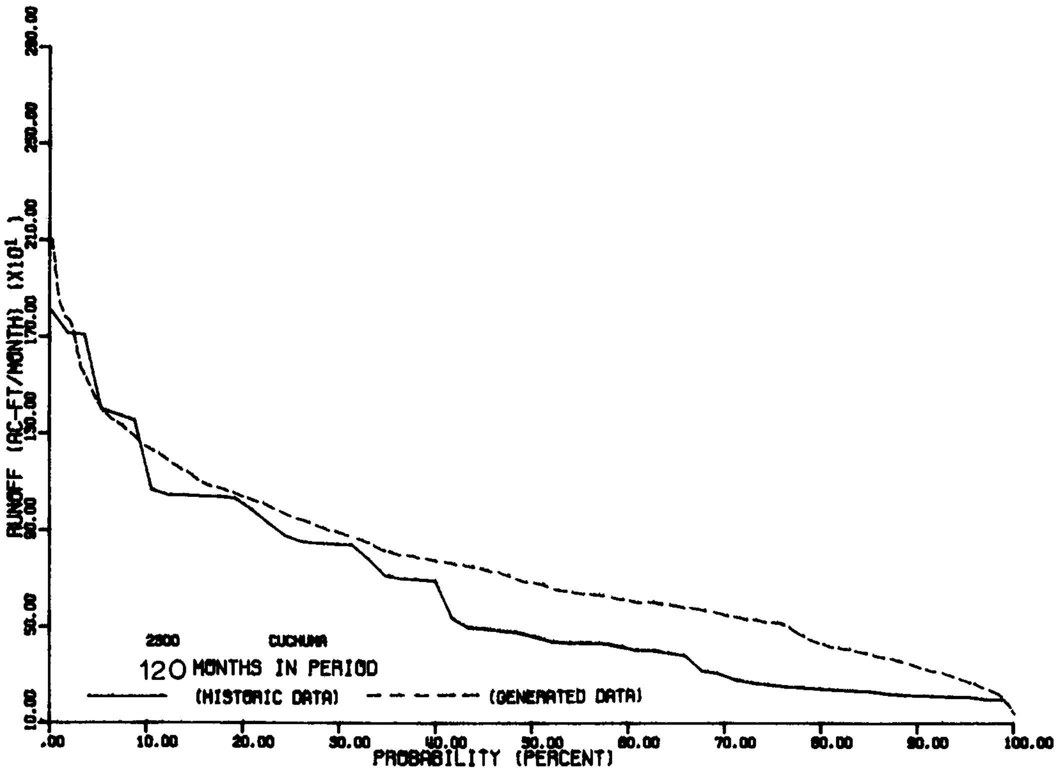

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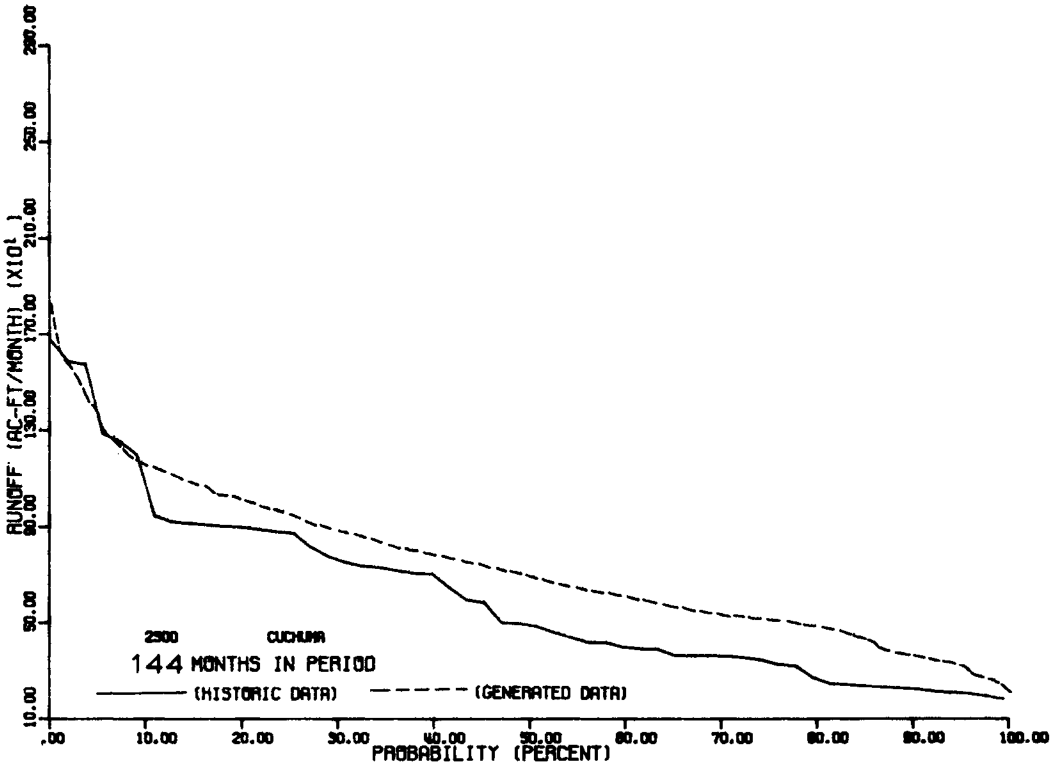

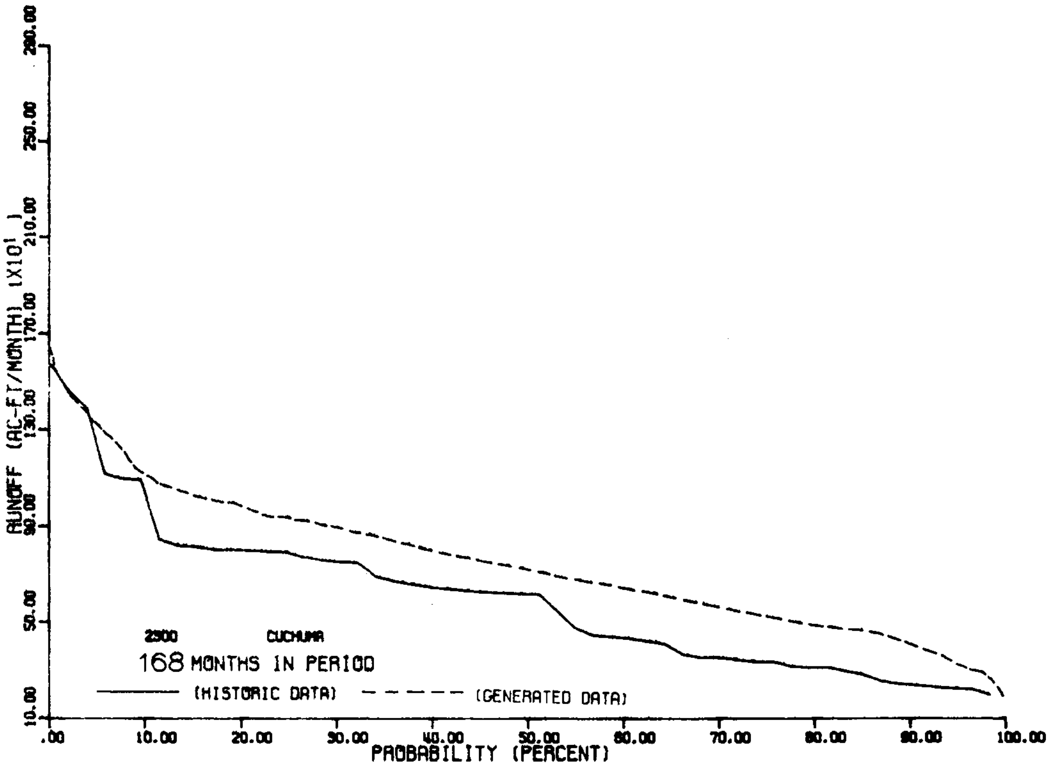

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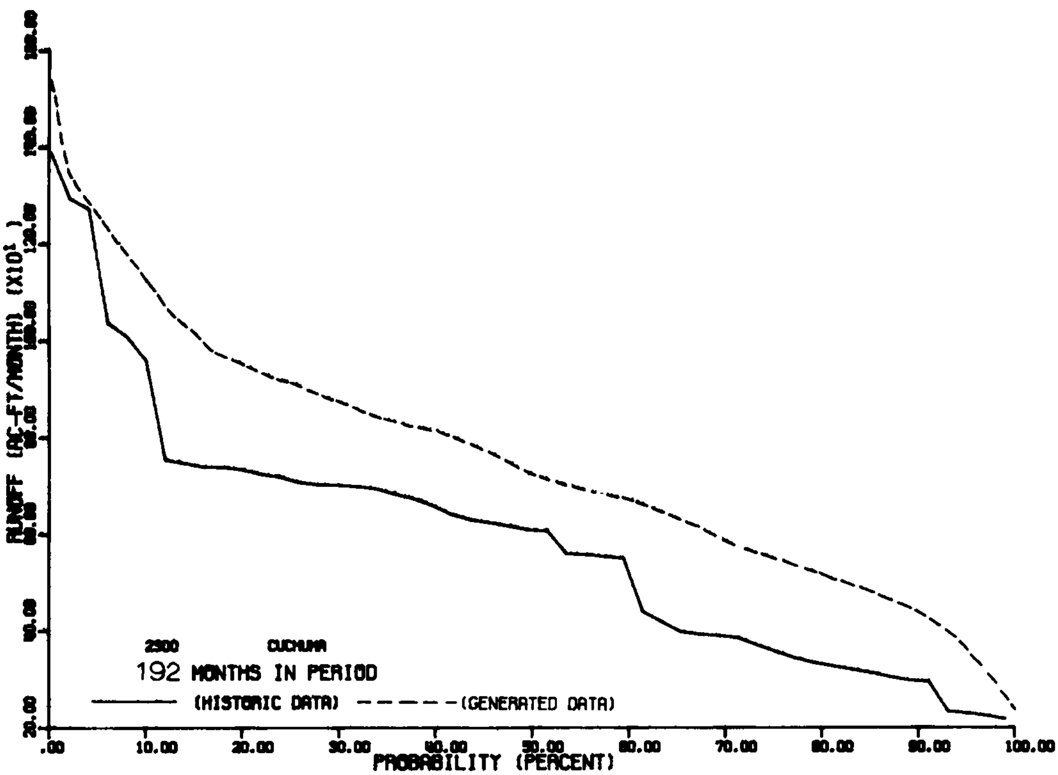


Figure 2. Concluded.

Schoharie Creek at Prattsville, New York

Monthly streamflow data for Schoharie Creek at Prattsville, New York were obtained for the period 1904 through 1967. These data are in terms of discharge in cubic feet per second, while the data for the other two streams are in terms of ac-ft per month. Fig. 3 contains the plotted results from the frequency analyses of the running averages over extended periods. Table 5 contains values of average discharge for the specified periods which might be expected to be exceeded for the four specified probabilities of occurrence. In contrast to the results of Cottonwood Creek, for the two low probabilities (i.e. the high flows), the averages obtained from the historic data are smaller than those obtained from the generated data, whereas, for the two larger percentages (i.e. the low flows), the historic averages are larger than the generated averages for the longer sequences.

Table 5. Average flowrate (cfs) for the given period of consecutive months that will be exceeded for four probabilities of occurrence. The flowrates are for both the historic and generated streamflow at Schoharie Creek at Prattsville, New York.

Period (Consecutive Months)	Probability of occurrence							
	2%		10%		90%		98%	
	Historic	Generated	Historic	Generated	Historic	Generated	Historic	Generated
24	611	662	543	566	347	340	276	301
48	532	598	516	529	382	367	297	332
72	527	574	496	515	400	383	317	351
96	504	554	489	509	407	392	352	365
120	498	550	485	501	412	399	366	379
144	489	545	480	495	422	407	398	385
168	481	532	474	490	431	411	406	390
192	478	521	470	487	436	413	420	397

Table 6, which contains the standard deviations of the running averages, also shows larger standard deviations for all sequences of generated data than the corresponding standard deviations from the historic data. The larger standard deviations further substantiate that for Schoharie Creek the generated data gives more critical periods for both sequences of high and low flows. This is the trend one would expect because 500 years of data generally will contain more severe droughts and also periods of high flow than the 64 years of historic data. In addition small differences in the standard deviations indicate that the frequency distribution of the running averages for the generated and historic data are very close. Consequently, the conclusion is that the operational hydrology program does a good job of reproducing long time trends in Schoharie Creek data, if any such trends are present.

Table 6. Comparison of standard deviations of running average data of streamflow at Schoharie Creek at Prattsville, New York. (Units are in cubic feet per second.)

No. of Consecutive Months	Standard deviations			
	Historic	Generated	Difference	Percent Difference
24	444.6	447.9	-3.3	.7
48	447.9	447.8	0.1	.0
72	450.2	447.8	2.2	.5
96	452.5	447.9	4.6	1.0
120	453.7	447.9	5.8	1.3
144	454.4	447.9	6.5	1.4
168	454.0	448.0	6.0	1.3
192	453.8	448.1	5.7	1.3

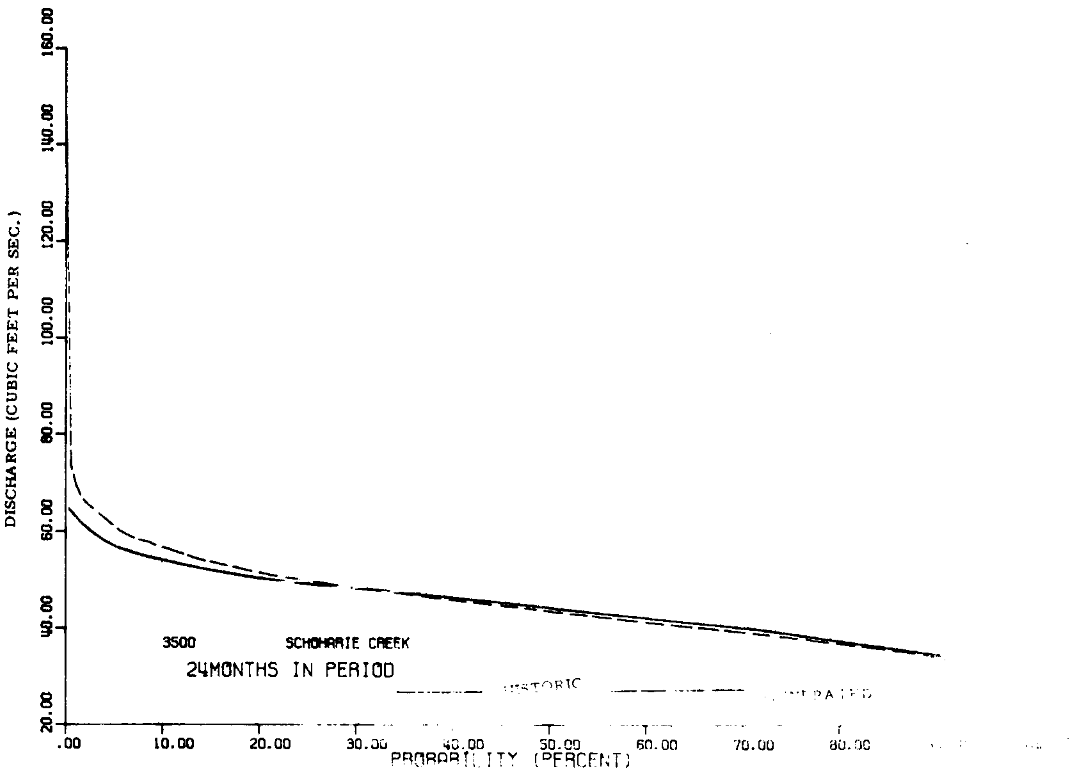
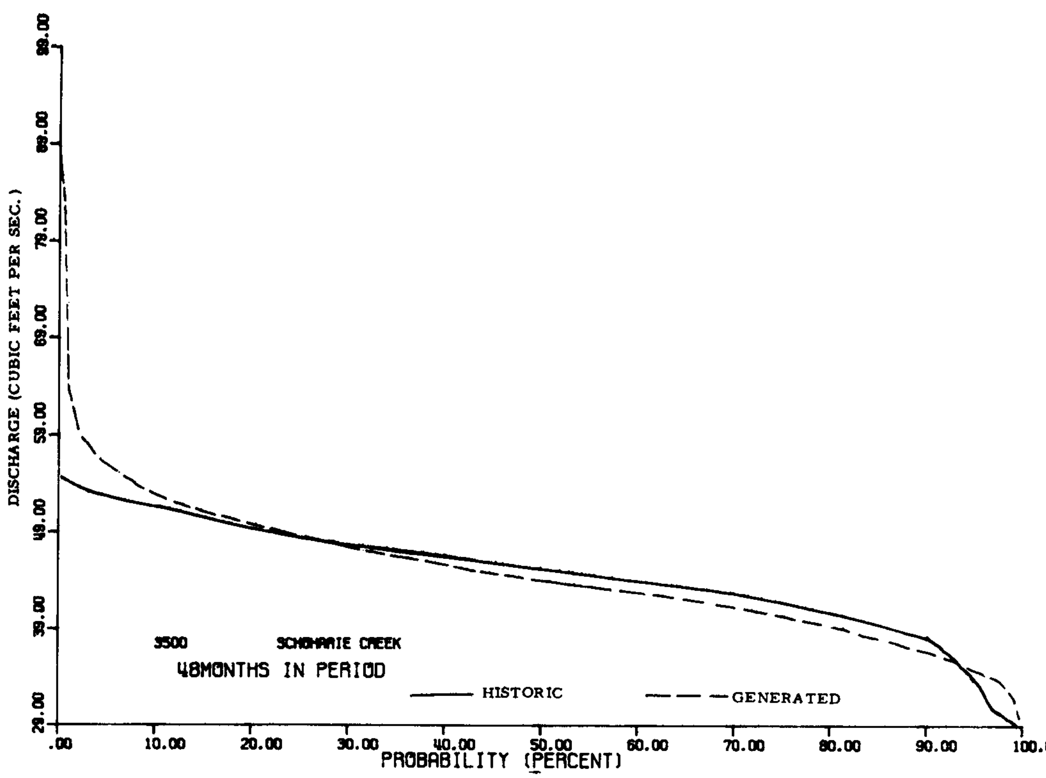


Figure 3. Relationships between average quantities of runoff over extended periods of time and probability of occurrence for Schoharie Creek, New York.



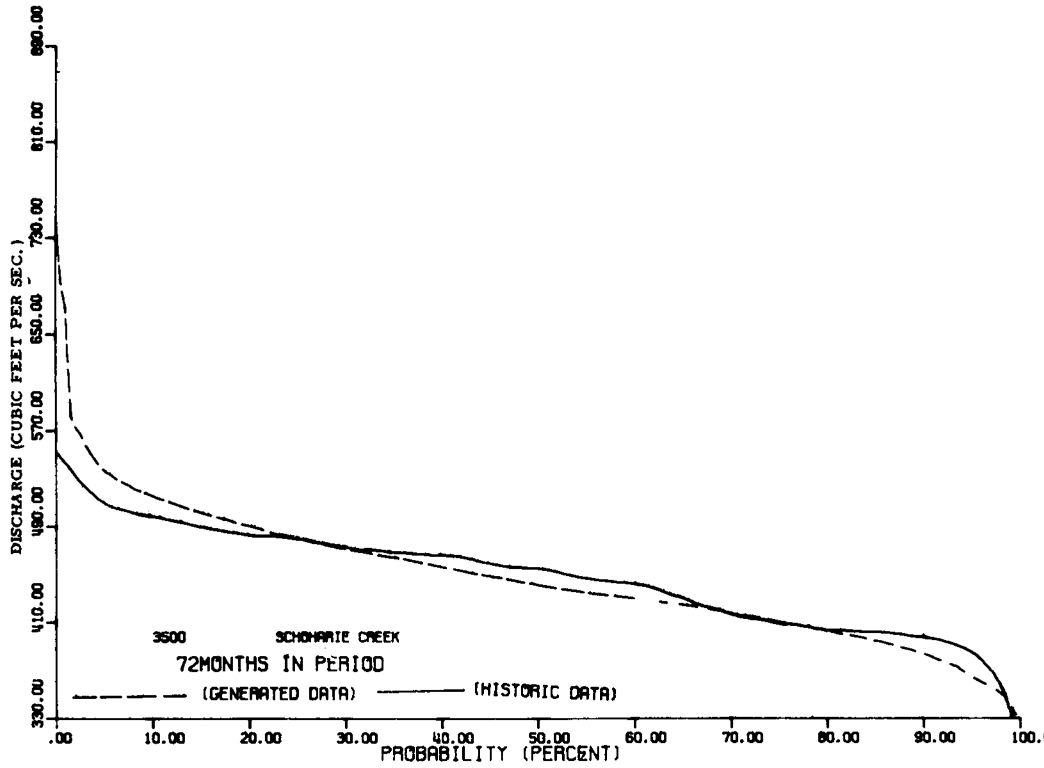
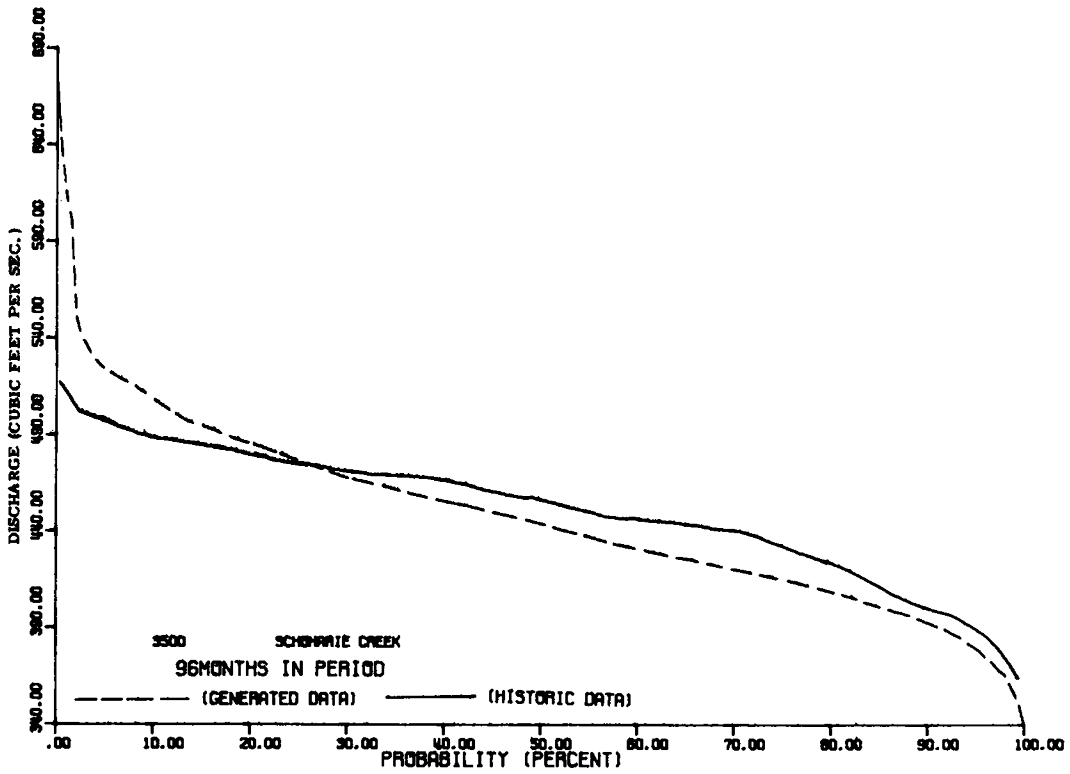


Figure 3. Continued.



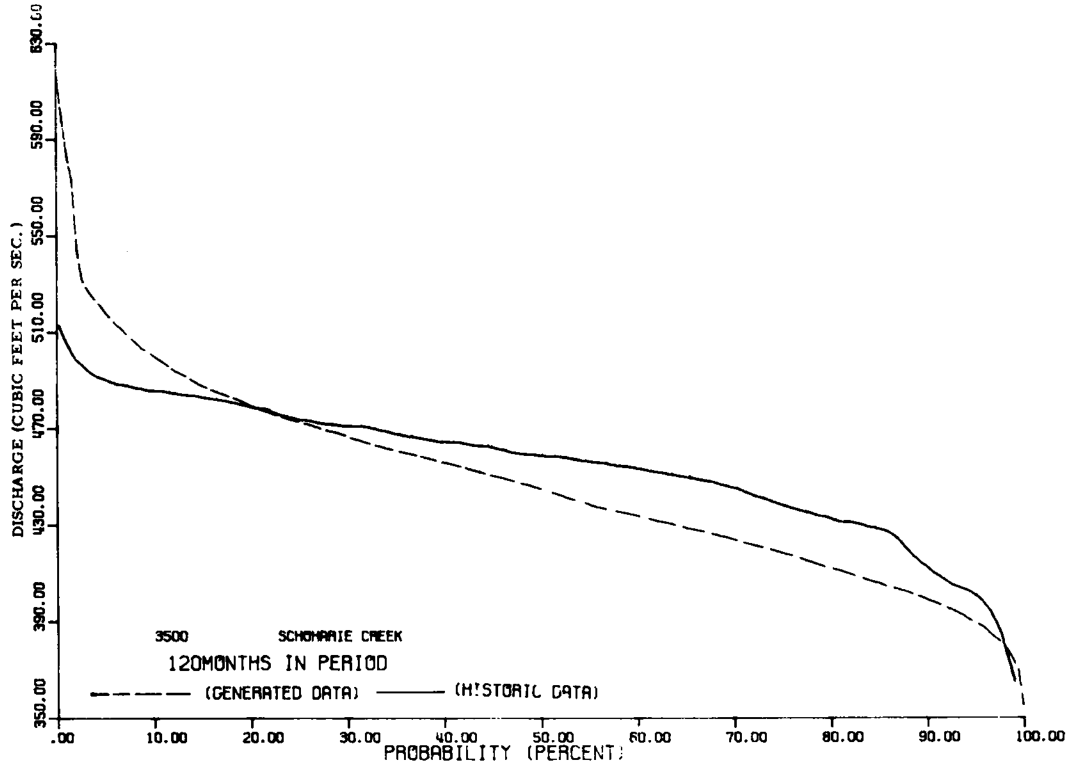
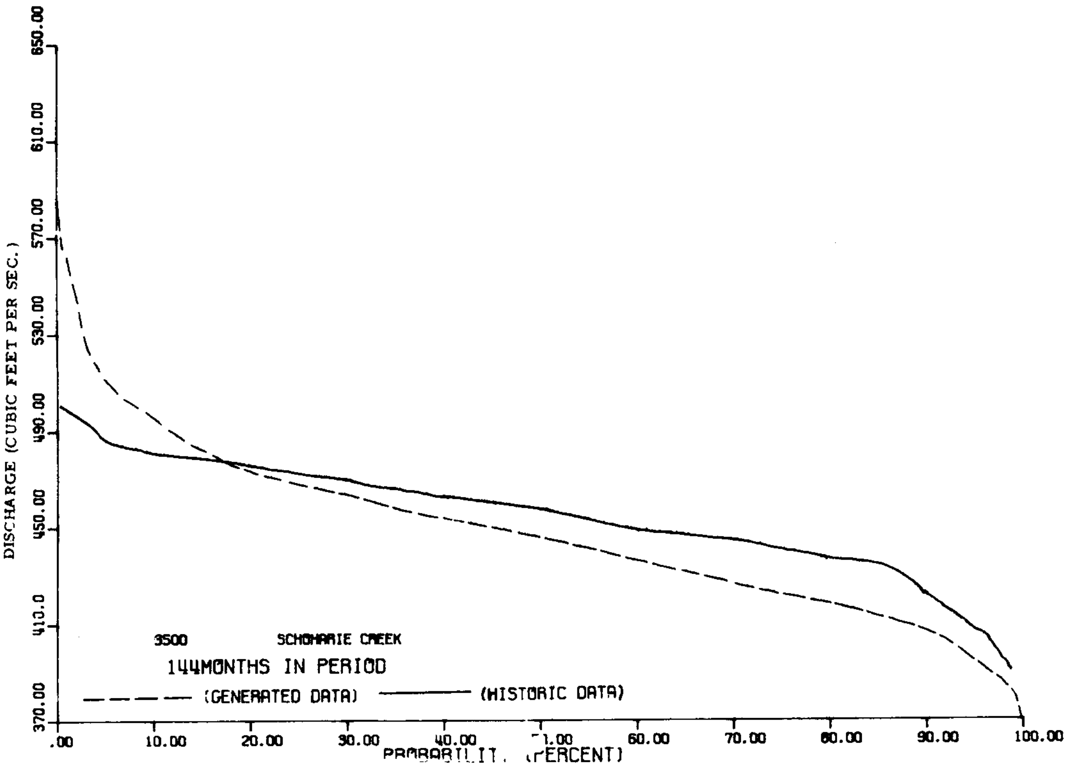


Figure 3. Continued.



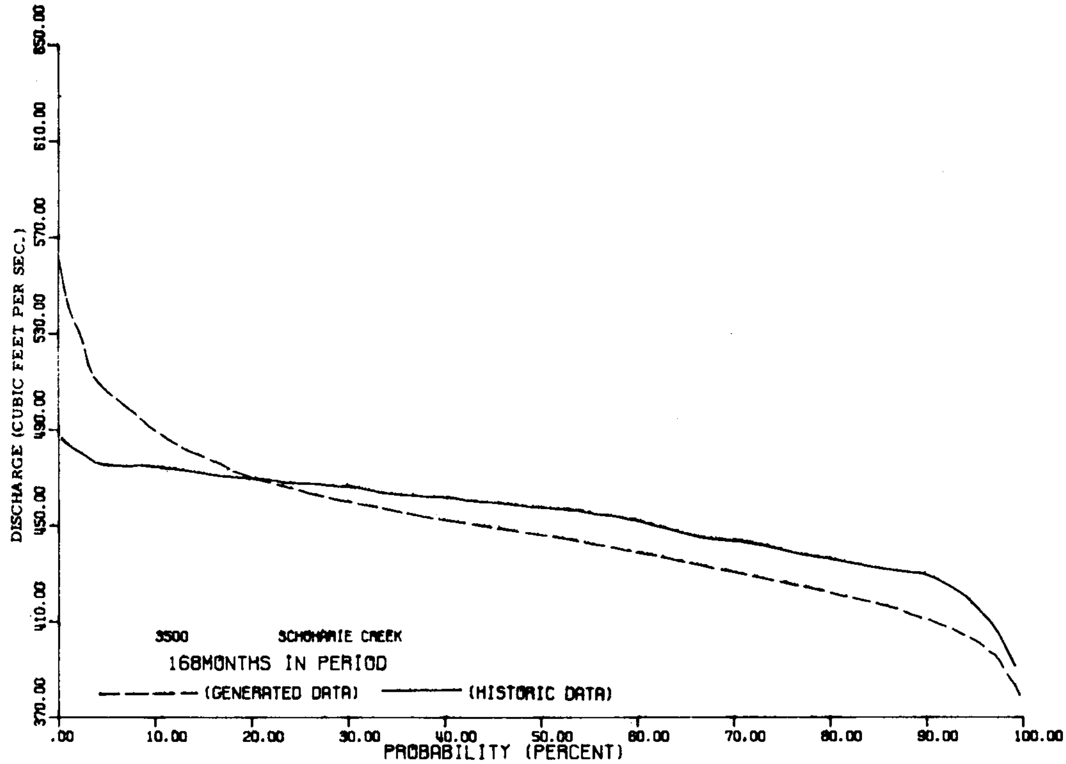


Figure 3. Continued.

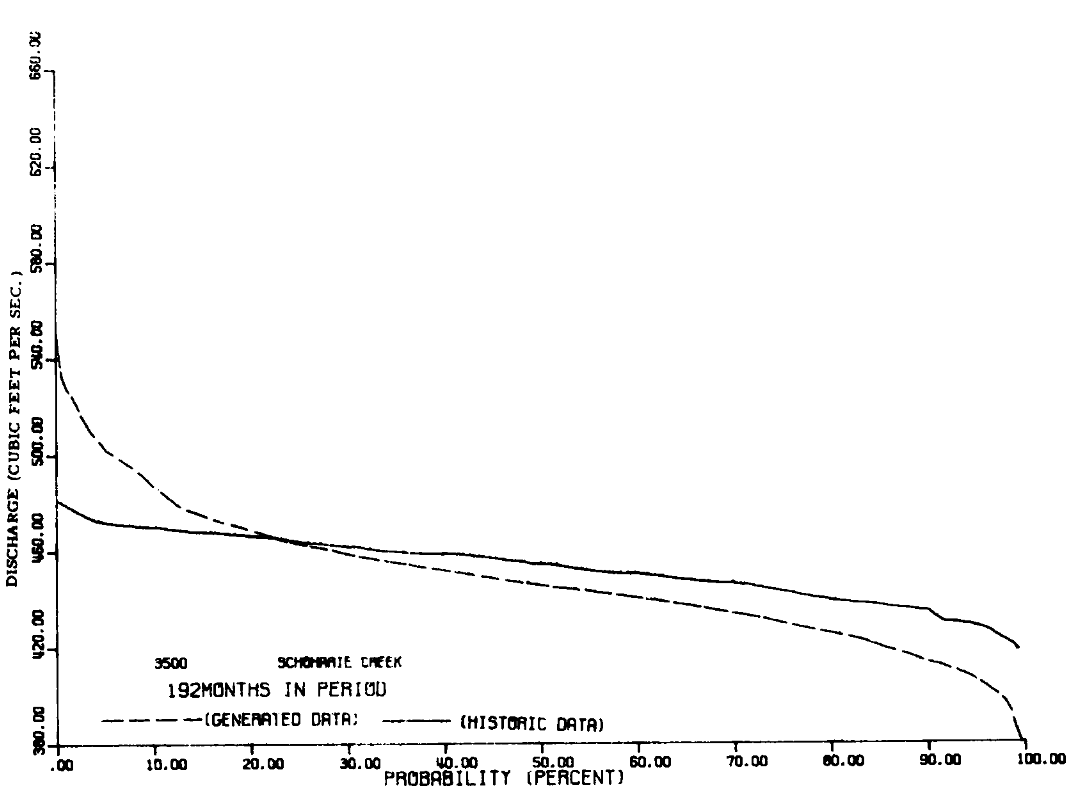


Figure 3. Concluded.

Summary

The development of operational hydrology techniques and computer programs is not static. Knowledge of the limitations of present operational hydrology programs will give incentive for overcoming these limitations. Progress toward this end has, without doubt, already occurred (see for example Mandelbrot and Wallis, 1968), and in the near future more improvements in methodology of generating streamflow will occur. It is expected that generated data for streams such as Cottonwood Creek near Orangeville, soon will be adequate in all respects.

The computer program listed in a latter section of this appendix gives a method of evaluating one aspect of streamflow operational hydrologies—namely, whether extended periods of historic high and low flows are duplicated in generated data. When used in conjunction with the program for analyzing the optimum operation of a desalting plant as a supplemental source of safe yield, the program on page 104 can help evaluate this aspect of the adequacy of the operational hydrology program. If the program does not reproduce extended periods of droughts or high flows adequately, then either another, more adequate program should be used to generate the streamflow data, or the conclusions about the economics of the supplemental desalted water should be modified by professional judgment in light of the degree of inadequacy of the generated streamflow.

Use, Description and Listing of Fortran Program

Data input required by program

The data cards read by the program consist of several control cards. Data containing the monthly values of streamflow are subsequently input. The program has been written for a system on which the FORTRAN logical unit 5 is the card reader and the control input parameters is through punched cards. The proper order of these control cards, containing the parameters which were used to evaluate the adequacy of the generated streamflow for Schoharie Creek at Prattsville, New York, is shown in Fig. 4. These control cards are as follows (unless stated otherwise all numbers are punched in the designated columns right-justified):

Card 1. The first control card contains the format of the monthly streamflow data in columns 1 through 72 left-justified. The FORTRAN logical unit containing the input monthly streamflow data is in columns 73 through 76, and the FORTRAN logical unit on which the output is to be written is in columns 77 through 80.

Card 2. The second control card specifies the number of periods of consecutive months that are to be analyzed and the length of each of these periods in months. The number of periods is contained in columns 1

```
|   99
TERMINATION OF THIS ACESS TO THE COMPUTER
```

CARDS CONTAINING GENERATED DATA (MAY BE ON ANY OTHER SPECIFIED INPUT UNIT)

```
    1 3500    1  500    0    1   10    0    1 236.0         2    1
NBASIN     NYRB     MISSNG     NPRIT     IPLOT         NGEN
      NSTA      NYRE       NPRT      NRIT     AREA          NCOMPR
  SCHOHARIE CREEK -- GENERATED DATA
```

CARDS CONTAINING HISTORIC DATA (MAY BE ON ANY OTHER SPECIFIED INPUT UNIT)

```
    1 3500    4   67    0    1   10    0    1 236.0         1    1
NBASIN     NYRB     MISSNG     NPRIT     IPLOT         NGEN
      NSTA      NYRE      KPRT      NRIT     AREA          NCOMPR
  SCHOHARIE CREEK AT PRATTSVILLE,N.Y.
```

NAME OF STREAM

```
    8   24   48   72   96  120  144  168  192
NO. OF      LENGTH OF EACH PERIOD IN MONTHS
PERIODS
(2X,I4,8X,12F5.1)                                        5     6
                                                      INPUT  OUT-
FORMAT OF INPUT DATA                                   UNIT   PUT
                                                              UNIT
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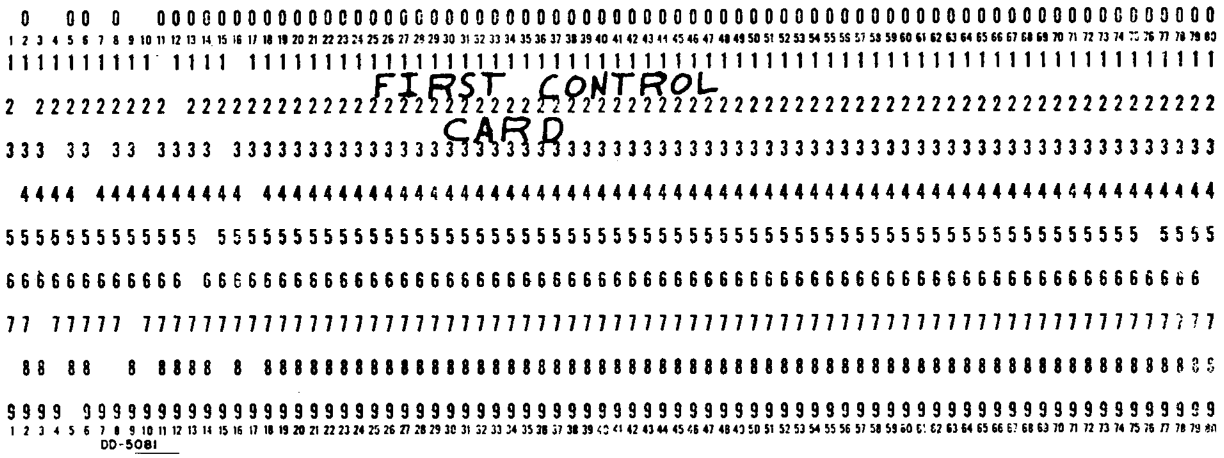

Figure 4. Example input for execution of program.

through 5, and with the present dimensions of the program must be equal to or less than 10. The lengths of each of these periods (given as number of consecutive months), are contained in the following columns of this card. Five columns are allocated for each number.

Card 3. The third card contains the name of the stream being investigated, and any other identification information desired in columns 1 through 72, left-justified.

Card 4. The fourth card contains several parameters which control the nature and amount of output as well as supply needed information about the data being analyzed. The name of each of these parameters as used in the FORTRAN program as well as its effect on the program are given in Table 7.

Streamflow. The streamflow data to be analyzed is required next by the program. This data may be punched on data cards. If so these cards follow the above control cards. The card reader must then be specified as the FORTRAN logical unit for data input. By specifying a tape unit, disk, drum or other input device, the streamflow data can be read from whatever input device this data is available on. The program contains a test to insure that the data for each year is for the specified station. This test requires that the station number precede the monthly data for that year. Should the station number be incorrect, execution is terminated. This portion of the program can readily be modified by deleting a few FORTRAN statements.

Any number of streamflow data can be analyzed by a single access to the computer. For each subsequent station's data (historic or generated) control cards 3 and 4 must be repeated. Should the format of the input data, its logical unit devices, or the number or lengths of consecutive months change for any subsequent station's data, then a card with any information followed by a card with 89 in columns 4 and 5 must precede the control cards beginning again with card 1 for that station. Execution is terminated by a card with any information followed by a card containing 99 punched in columns 4 and 5.

Table 7. Control parameters on input data card no. 4.

Variable Name	Col's Containing Information	Information Contained in Parameter or Effect of Parameter
NBASIN	1-5	is the river basin number of the streamflow data.
NSTA	6-10	is the number assigned to the streamflow data.
NYRB	11-15	is the beginning year of the streamflow data.
NYRE	16-20	is the final year of the streamflow data.
MISSING	21-25	is the number of missing years of data in the streamflow data.
KPRT	26-30	is a parameter, which if assigned a value greater than 0 suppresses the writing of all the running average data which are computed for all possible consecutive months. The ranked running averages, their probabilities and ranked number are also printed.
NPRIT	31-35	determines how many of the running average data are written. For example if NPRIT equals 10 every tenth value is printed along with its probability of occurrence. If KPRT equals zero this data is not written separate from the data already written.
NRIT	36-40	determines whether the input streamflow data is to be written or not. If NRIT equals 0 the input streamflow data is written.
IPLOT	41-45	if IPLOT is greater than zero the subroutine PLTTR is called which writes a plot tape for plotting the results from the frequency distribution of the running averages, in order of high to lower values of streamflow. The subroutine PLTTR must be altered as necessary to call plot subroutines implemented on the particular system being used.
AREA	46-55	is the area of the watershed contributing to the streamflow in square miles.
NGEN	56-60	is a parameter which determines whether the streamflow data is the historic data or the data obtained from an operational hydrology program. NGEN must equal 1 if historic data is input and must equal 2 if operational hydrology data is input.
NCOMPR	61-65	if a table comparing the historic and generated data is to be written NCOMPR should be greater than zero. Otherwise NCOMPR should be assigned zero. If NCOMPR is greater than zero, it is necessary to follow the historic data by operational hydrology data in the same access to the program.

Other variables used in computer program

FSUM	double precision value used to temporarily store running average values
S	used to obtain sums of the running averages
S2	used to obtain sum of differences squared between average and individual running averages
S3	used to obtain sum of difference cubed
FNID	double precision value of the number of years of data
DIF	difference
FNIDM	FNID - 1.0
DIF2	difference squared
RM	two-dimensional array used to store monthly streamflow data, and annual values
NAME	array for storing the name of stream gaging station
FMT	array for storing format of streamflow data
SUMA	array for storing individual running averages which are computed from the streamflow data
SUMA1	array for storing ranked values of SUMA
SUMA2	array for storing a selected number of SUMA1
PRBOL	array for storing probabilities corresponding to values in SUMA2
STAD	two-dimensional array for storing standard deviations
MEANR	two-dimensional array for storing means
NPER	array for storing length of periods of consecutive months which are to be analyzed
NPERID	number of periods NPER
NI & NYRS	number of years of streamflow data. NI latter in the program also represents the number of computed running averages
RMM	used to compute annual streamflow
NYREM	NYRE - 1
FAC	factor to convert ac-ft to equivalent inches of depth over the watershed
NCOUNT	index to accumulate number of running averages
SUM	variable used to obtain running averages
FNI	floated value of NI
TP	recurrence interval
VAR	variance
STD	standard deviation
SKEW	skewness coefficient
AUM	average standard deviation
T	value to compare with statical t-distribution

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Mandelbrot, B. B. and J. R. Wallis. 1968. Water Resources Research, Vol. 4, No. 5, October, pp. 909-918.

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LISTING OF FORTRAN PROGRAM

```
'I  FOR STRENF,STRENF
      DOUBLE PRECISION   FSUM,S,S2,S3,FNID,DIF,FNIDM ,DIF2
      DATA DASH/6H------/
      REAL RM(500,13),NAME(12),FMT(12),SUMA(6000),SUMA1(6000),SUMA2(793)
     $,PRBOL(793),STAD(10,2),MEANR(10,2),SUMAN(80,10),PRBON(80,10),OPID(
     $4)
      INTEGER NPER(10),IIIN(10)
   98 READ(5,143) (FMT(I),I=1,12),NREAD,NWRITE
  143 FORMAT(12A6,2I4)
      READ(5,102) NPERID,(NPER(I),I=1,NPERID)
  102 FORMAT(11I5)
   10 READ(5,143)(NAME(I),I=1,12)
      READ(5,100) NBASIN,NSTA,NYRB,NYRE,MISSNG,KPRT,NPRIT,NRIT,IPLOT,
     $AREA,NGEN,NCOMPR
  100 FORMAT(9I5, F10.5,3I5)
      IF(IPLOT .GT. 0) READ(5,133) ORID
  133 FORMAT(4A6)
C   NGEN=1 IF HISTORIC DATAA = 2 IF GENERATED DATA
C    NCOMPR   IF COMPARISON BETWEEN HISTORIC AND GENERATED DATA IS TO BE MADE THE
C VALUE OF NCOMPR SHOULD NOT BE EQUAL TO 0, HISTORIC DATA SHOULD BE FIRST
      IF(NBASIN .EQ. 99) GO TO 99
      IF(NBASIN .EQ. 89) GO TO 98
      NI=NYRE-NYRB+1-MISSNG
      NYRS=NI
      DO 1 I=1,NI
      READ(NREAD,FMT) NUB,(RM(I,J),J=1,12)
      IF(NUB .EQ. NSTA) GO TO 1
      II=I
      GO TO 998
    1 CONTINUE
 2588 DO 63 I=1,NI
      RMM=0.0
      DO 64 J=1,12
   64 RMM=RMM+RM(I,J)
   63 RM(I,13)=RMM
      IF(NRIT .GT. 0) GO TO 62
      NYREM=NYRB-1
      DO 1582 I=1,NI
      II=NYREM+I
 1582 WRITE(NWRITE,1583) II,(RM(I,J),J=1,13)
 1583 FORMAT(1H ,I4,4F9.1,9F10.1)
   62 FAC=0.01875/AREA
   44 DO 2 IK=1,NPERID
      I1=1
      J1=1
      NP=NPER(IK)
      NP1=NP-1
      FNP=NP
      NIE=12*NYRS-NP1
      SUM=0.0
      NCOUNT=1
      IE=NP1/12
      IE1=IE+1
      JE=MOD(NP1,12)+1
      IF(IE .EQ. 0) GO TO 4
      DO 3 I=1,IE
      DO 3 J=1,12
    3 SUM=SUM+RM(I,J)
    4 DO 8 J=1,JE
    8 SUM=SUM+RM(IE1,J)
      SUM=SUM/FNP
      SUMA(NCOUNT)=SUM
      SUMA1(NCOUNT)=SUM
    5 JE=JE+1
      IF(JE-12) 9,9,20
   20 IE1=IE1+1
      JE=1
    9 SUM=SUM+(RM(IE1,JE)-RM(I1,J1))/FNP
      NCOUNT=NCOUNT+1
      SUMA(NCOUNT)=SUM
      SUMA1(NCOUNT)=SUM
      J1=J1+1
      IF(J1-12) 11,11,12
   12 I1=I1+1
      J1=1
   11 IF(NCOUNT .LT. NIE) GO TO 5
      NI=NCOUNT
      FNI=NI
      FNIM=FNI-1.0
      FNID=FNI
      FNIDM=FNID-1.0D00
      FNI1=100./(FNI+1.0)
      M=NI
  314 M=M/2
      IF(M) 322,322,316
  316 K=NI-M
      JJ=1
  317 I=JJ
  318 L=I+M
      IF(SUMA1(L)-SUMA1(I)) 321,321,320
  320 B=SUMA1(I)
      SUMA1(I)=SUMA1(L)
      SUMA1(L)=B
      I=I-M
      IF(I-1) 321,318,318
  321 JJ=JJ+1
      IF(JJ-K) 317,317,314
  322 CONTINUE
      WRITE(NWRITE,101) NBASIN,NSTA,NP,(NAME(I),I=1,11)
  101 FORMAT(1H0,//31H FREQUENCY ANALYSIS FOR STATION,I3,1H-,I4,17H FOR
     $A PERIOD OF ,I3,7H MONTHS,11A6)
      IF(KPRT .GT. 0) GO TO 73
      WRITE(NWRITE,112)
  112 FORMAT(1H0,64H       AV. RUNOFF        RANKED RUNOFF        RECUR.
     $     PROB.  )
      WRITE(NWRITE,103)
  103 FORMAT(1H ,66H     AC-FT/MO  INCHES  AC-FT/MO INCHES        INTER.
     $      LEVEL     )
   73 S=0.0
      S2=0.0
      S3=0.0
      PRB1=0.0
      FSUMP=0.0
      IP=1
      III1=0
      DO 56 I=1,NI
      FSUM=SUMA1(I)
   56 S=S+FSUM
      AS=S/FNID
      DO 55 I=1,NI
      FI=I
      TP=FN1/FI
      FRB=FNI1*FI
      PRB1=PRB
      IF(MOD(I-1,NPRIT) .NE. 0) GO TO 1754
      III1=III1+1
      IF(NGEN .EQ. 2) GO TO 1821
      PRBON(III1,IK)=PRB
```

```
      SUMAN(III1,IK)=SUMA1(I)
 1821 PRBOL(III1)=PRB
      SUMA2(III1)=SUMA1(I)
 1754 FSUM=SUMA1(I)
      DIF=FSUM-AS
      DIF2=DIF*DIF
      S2=S2+DIF2
      S3=S3+DIF2*DIF
      IF(KPRT .GT. 0) GO TO 55
      FSUM1=FAC*SUMA(I)
      FSUM2=FAC*SUMA1(I)
      WRITE(NWRITE,110) I,SUMA(I) ,FSUM1,SUMA1(I),FSUM2,TP,PRB
   55 CONTINUE
      IF(NGEN .EQ. 1) IIIN(IK)=III1
  110 FORMAT(1H ,I3,2(F10.2,F 7.4),5X,2F10.2)
 1571 FNIM=FNI-1.0
      VAR=S2/FNIDM
      STD=SQRT(VAR)
      SKEW=FNID*S3/(FNIDM*S2)
      SKEW=SKEW/(STD*(FNI-2.))
      WRITE(NWRITE,121) AS,VAR,STD,SKEW
  121 FORMAT(4H AV=,F12.2,5H VAR=,F12.2,5H STD=,F12.2,6H SKEW=,2E14.5)
      IF(KPRT .EQ. 0) GO TO 2021
      WRITE(NWRITE,1679)
 1679 FORMAT(1H0, /,' PROBABALITY AND MAGNITUDES OF RUNOFF' )
      NM1=1
      NM2=13
 1676 IF(NM2 .GT. III1) NM2=III1
      WRITE(NWRITE,1674) (PRBOL(I),I=NM1,NM2)
      WRITE(NWRITE,1675) (SUMA2(I),I=NM1,NM2)
 1674 FORMAT(1H0,13F10.3)
 1675 FORMAT(1H ,13F10.1)
      IF(NM2 .EQ. III1) GO TO 2021
      NM1=NM1+13
      NM2=NM2+13
      GO TO 1676
 2021 STAD(IK,NGEN)=STD
      MEANR(IK,NGEN)=AS
      IF(IPLOT.GT.0 .AND. NGEN.EQ.2) CALL PLTTR(SUMA2,PRBOL,SUMAN,PRBON,
     $ORID,III1,IIIN,NSTA,NAME,NP,IK)
    2 CONTINUE
      IF(NCOMPR .EQ. 0 .OR. NGEN .EQ. 1) GO TO 10
      WRITE(NWRITE,1687)
      WRITE(NWRITE,1688)
      SUM=0.0
      SUM2=0.0
 1687 FORMAT('1PERIOD          STANDARD DEVIATIONS ')
 1688 FORMAT(' MONTHS     HISTORIC     GENERATED  DIFF. PERCENT DIFF.'
      WRITE(NWRITE,1690) (DASH,J=1,9)
 1690 FORMAT(1H ,9A6)
      DO 1686 IK=1,NPERID
      DFF=STAD(IK,1)-STAD(IK,2)
      PDFF=100.*DFF/STAD(IK,1)
      WRITE(NWRITE,1689) NPER(IK),STAD(IK,1),STAD(IK,2),DFF,PDFF
 1689 FORMAT(1H ,I5,4F12.2)
      SUM=SUM+DFF
 1686 SUM2=SUM2+DFF*DFF
      WRITE(NWRITE,1690) (DASH,J=1,9)
      PERID=NPERID
      AUM=SUM/PERID
      VAR=(SUM2-AUM*SUM)/(PERID-1.0)
      STD=SQRT(VAR)
      T=AUM*SQRT(PERID)/STD
      WRITE(NWRITE,1691) AUM,STD
 1691 FORMAT(16X,'AVERAGE DIFF. =',F12.2, / 16X,'STANDARD DEV.=',F12.2)
      WRITE(NWRITE,1692) T
 1692 FORMAT( ' STATISTICAL  T-VALUE EQUALS ,' F12.2)
      WRITE(NWRITE,1787)
      WRITE(NWRITE,1688)
 1787 FORMAT(/,/,'0PERIOD  MEANS OF RUNNING AVERAGES')
      WRITE(NWRITE,1690) (DASH,J=1,9)
      DO 1786 IK=1,NPERID
      DFF=MEANR(IK,1)-MEANR(IK,2)
      PDFF=100.*DFF/MEANR(IK,1)
      WRITE(NWRITE,1689) NPER(IK),MEANR(IK,1),MEANR(IK,2),DFF,PDFF
 1786 CONTINUE
      WRITE(NWRITE,1690) (DASH,J=1,9)
      GO TO 10
  998 WRITE(6,999) NSTA,NUB,(RM(II,J),J=1,12)
  999 FORMAT(' INCORRECT DATA FOR STA.',I5,I5,12F8.3)
   99 STOP
      END
'I  FOR PLTTRF,PLTTRF
      SUBROUTINE PLTTR(Y,P,Y1,P1,ORID,NI,NN,NSTA,NAME,LP,KK)
      REAL Y(793),P(793),NAME(12),Y1(80,10),P1(80,10),ORID(4),YS1(80),
     $PS1(80)
      INTEGER NN(10)
      KKP=NN(KK)
      DO 3 I=1,KKP
      YS1(I)=Y1(I,KK)
    3 PS1(I)=P1(I,KK)
      ALX=10.0
      ALY=7.0
      CALL IDPLOT(ALX+1.5,ALY+1.5)
      IF(LP.EQ.24) CALL SYMBL4(.2,0.0,.10,58HMAIL TO R.W.JEPPSON,UWRL,UT
     $AH STATE UNIV.,LOGAN,UTAH,84321,90.0,58)
      CALL SCALE(P,NI,ALX,XMIN,DVX,1)
      CALL SCALE(Y,NI,ALY,YMIN,DVY,1)
      CALL PLOT(1.0,1.0,-3)
      CALL AXIS(0.0,0.0,22H PROBABILITY (PERCENT),-22,ALX,0.0,0.0,DVX)
      CALL AXIS(0.0,0.0,ORID,24,ALY,90.0,YMIN,DVY)
      CALL LINE(P,Y,NI,1)
      CALL LINE(PS1,YS1,KKP,1)
      CALL NUMBRI(0.5,0.8,.12,NSTA,0.0)
      CALL SYMBL4(2.2,.8,.12,NAME,0.0,30)
   11 CALL NUMBRI(0.3,0.5,.14,LP,0.0)
      CALL SYMBL4(1.5,0.5,.14,17H MONTHS IN PERIOD,0.0,17)
      CALL PLOT(-1.0,-1.0,-3)
      CALL FINI
      RETURN
      END
'N XQT STRENF
(2X,I4,8X,12F5.0)
   8   24   48   72   96  120  144  168  192
 COTTONWOOD CREEK
   9 3245   10   65    0    1   10    1    0 205.          1    1
 93245       1910 2790 2300 2220 1840 1670 5590170003730019500 5600 2900 4870103580
 93245       1911 1540 1900 1840 1840 2170 5920 49003020027100 5120 2470 2460 87460
 93245       1912 1730 1570 1540  861  667 1530 24901540052400135 00 3690 2270 97648
 93245       1913 2030 1790 1230 1540 1390 1840 75604370023900 6820 3110 6190101100
 93245       1914 1780 1570 1750 1650 1560 2230 58704460041300129 00 3920 2610121740
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APPENDIX C

DESALTING COST DATA

TABLE OF CONTENTS

OAK RIDGE NATIONAL LABORATORY
OPERATED BY
UNION CARBIDE CORPORATION
NUCLEAR DIVISION

POST OFFICE BOX X
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Special Distribution

ORNL
CENTRAL FILES NUMBER
69-4-20

DATE: April 7, 1969 COPY NO. 35

SUBJECT: Design and Cost Data on Water-Only MSF Desalting Plants for Use in Conjunctive Water System Economic and Feasibility Studies

TO: Distribution

FROM: H. R. Payne

ABSTRACT

The results of a cost study on MSF desalting plants for conjunctive water systems are presented. These are water only plants of 25, 50, 75 and 100 Mgd capacity operating at plant factors of 10, 20, 30, 50, 70 and 90%. The design and costs for an optimized plant of each size and plant factor, including a steam plant, is determined using the MSF 21 computer program. The cost of water from each of the optimized plants is then determined with it operating at each of the other 5 plant factors. Included are costs for the startup-shutdown and mothballing required in a conjunctive system.

The annual cost, total unit water cost, and unit fuel cost for 144 cases are presented in tabular form. Detailed design and cost data for the 50 Mgd plant at 90% PF are given and the basic design data and costs for the 24 optimized plants are given. Curves show cost trends for each plant size as a function of the plant factor at which the plant was optimized and the operating plant factor.

This work is a portion of OSW W. O. 35.

DESALTING COST DATA

Introduction

One application for desalting plants is in conjunctive use with conventional surface water supplies. Conjunctive use implies the operation of the desalting plant during periods of drought or at other times when the reservoir levels are subnormal. It has been postulated that the construction of partly-firm water-works plus conjunctive desalting plants may be more economical than the construction of larger water-works which guarantee firm yield of the same total water supply.

Under a contract between Utah State University and OSW to study operating rules for conjunctive systems, the following objectives are listed:

1. To determine the optimum fashion in which to operate desalting plants to provide supplemental safe yield.

2. To assess the impact of such operation on the performance characteristics and design of a desalting plant used in this service as well as in the identification of unique operating features of the plant.

3. To program the relationships of the above mentioned objectives 1 and 2 so that the digital computer output can be conveniently used to assess alternatives and aid in decision making.

ORNL was asked to provide Utah State University with estimates of multistage flash plant capital and operating costs. Plants were optimized with the MSF21 computer program developed for OSW, with costs revised in December 1968. The designs are based on current commercial practice; thus the costs should be a reasonable estimate of present day costs. The four sizes included in this study are 25, 50, 75 and 100 Mgd. In conjunctive use the desirable plant load factor may range from 0 to 100 percent. The upper limit is unobtainable, so for practical reasons, a range of 10 percent to 90 percent was used.

Ground Rules and Basis for Costs and Design

1. Size of plants–25, 50, 75 and 100 Mgd.
2. Plant load factors–10%, 20%, 30%, 50%, 70% and 90%.
3. Determine the cost of water from a plant of each of the above sizes optimized at each of the above plant factors (24 cases).
4. Determine the cost of water for each of the optimized plants operating at each of the other 5 plant factors (120 cases).
5. Water-only plants.
6. Fuel cost of 35¢/MBtu.
7. Interest rate of 4 5/8%, 30 year plant life.
8. Include capital and operating cost of steam supply.
9. Include cost for startup, shutdown, and mothballing of evaporators.
10. Use Base Line 50 Mgd as a basis for water plant design and cost.
11. Fix the following parameters before optimizing the 24 base cases.
    a. Number of plant levels = 1.
    b. OD of heater tubing = 0.75 in.
    c. OD of recovery tubing = 0.75 in.
    d. OD of reject tubing = 0.75 in.
    e. Wall thickness of heater, recovery and reject tubing = 0.049 in.
    f. Concentration ratio = 2.
    g. Maximum specific tray flow rate = 8×10^5 lb/hr-ft.
    h. Feedwater temperature = 61 °F.

Cost of Steam

The capital cost of the steam plant is based on information in OSW R&D Report No. 257. An equation developed defining the cost as a function of the megawatts thermal supplied to water plant was added to the computer program MSF21 for this study. This equation is:

$$C = 42.72 \times 10^3 \ (MWt)^{.8388} \$$$

where:
C = total capital cost including indirects
MWt = heat supplied to water plant in megawatts

The annual fuel cost is a function of the plant factor, water plant size, performance ratio and delivered fuel cost. Using a furnace stack efficiency of 85 percent and fuel cost of 35¢/ MBtu, the following equation for the annual fuel cost was added to the computer program.

$$C_f = 1253.5 \times 10^3 \times \frac{MxPF}{R} \ \$/yr$$

where:

M = water plant size in Mgd
PF = plant load factor
R = performance ratio.

Operating labor for the steam plant is estimated to be equal to 35 percent of the water plant operating labor. Maintenance labor is a function of capital cost and plant factor. For a plant operating full time (90% PF), it is 0.6 percent of the capital cost. It is related to the plant factor by multiplying it by a factor equal to (.1+PF). Thus for a plant operating full time (90% PF), this factor is 1.

Cost of Startup, Shutdown, and Storage

All plants are assumed to be equipped with a nitrogen flooding facility. When mothballed the plant will be drained, flushed, and flooded with nitrogen. The nitrogen will be maintained at a very slight positive pressure during the storage period. Table 1 lists the capital cost for the nitrogen flushing system.

It is assumed that operating and maintenance labor costs are increased as a result of intermittent operation. This will vary with plant size and plant factor (inversely). The estimated annual cost for this, plus the annual cost of the nitrogen system and nitrogen are summed and presented in Table 2. The cost for the 90 percent plant factor includes only the nitrogen system and nitrogen. The estimated annual cost is rounded to the nearest $1,000. The equivalent unit cost is given in Table 3.

Design and Cost of the Optimized Plants

Table 4 gives in some detail the design and cost data for the 50 Mgd MSF plant of this study optimized at a plant factor of 90 percent. The costs and basic design data of the 24 optimized plants are shown in Table 5.

The unit fuel costs are shown on Tables 6 through 9 so the effect on the total is readily apparent. This cost becomes an increasing fraction of the total as the plant factor increases.

Figures 1 through 4 give a picture of the cost trends for plants optimized at 10, 50, and 90 percent plant factors and operating over the range of 10 to 90 percent.

Cost of Water

From the annual operating costs shown in Table 5, the unit costs of water are calculated and shown in Tables 6 through 9. The costs of water from the optimized plants operating at the other plant factors included in this study are also given in these tables.

As the plant factor increases the optimum performance ratio increases. This gives a corresponding increase in capital cost which in terms of unit cost is more than offset by the increased production.

The operating and maintenance labor are assumed to vary with the plant factor in the same manner as for the steam supply. This also contributes to a decreasing unit cost as the plant factor increases.

Conclusion

As expected the unit cost of water from the desalting plants decreased with increasing size and plant factor. When these plants are considered as part of a conjunctive system, a completely different effect on the overall cost of water would result.

As stated in the ground rules, only one fuel cost and interest rate is used. Their share (fuel and fixed charges) of the cost can be readily adjusted for other values which, if not greatly different, will still yield reasonable estimates for the total cost of water from these desalting plants. Thus, this information can be used in a wide range of conjunctive water system cost studies.

TABLE 1

Capital Cost of Nitrogen Flooding System

	Plant Size			
	25 $	50 $	75 $	100 $
N_2 Storage Facility	40,000	40,000	40,000	40,000
Piping and Crossover for Adding Nitrogen	5,000	5,000	5,000	5,000
Special Valves & Controls for Flushing	20,000	20,000	20,000	20,000
First Change of N_2	900	1,800	2,700	3,600
Total	65,900	71,800	80,200	86,100

TABLE 2

Annual Cost of Nitrogen System, Nitrogen, Startup, Shutdown, and Storage

Plant Factor	Plant Size-Mgd			
	25	50	75	100
%	$/yr	$/yr	$/yr	$/yr
10	46,000	69,000	95,000	117,000
20	44,000	67,000	93,000	113,000
30	41,000	62,000	89,000	109,000
50	37,000	56,000	82,000	100,000
70	33,000	50,000	76,000	90,000
90	5,000	5,000	6,000	6,000

Note: Except for 90% plant factor, costs include one startup-shutdown cycle per year.

TABLE 3

Unit Cost of Nitrogen System, Nitrogen, Startup, Shutdown, and Storage

Plant Factor	Plant Size-Mgd			
	25	50	75	100
%	¢/kgal	¢/kgal	¢/kgal	¢/kgal
10	5.04	3.78	3.47	3.2
20	2.41	1.84	1.70	1.55
30	1.5	1.31	1.08	1.0
50	0.81	0.62	0.60	0.55
70	0.51	0.39	0.40	0.35
90	0.06	0.03	0.02	0.02

Note: Except for 90% plant factor, costs include one startup-shutdown cycle per year.

TABLE 4

Typical Cost and Design Values for an Optimized MSF Plant. These values are for a 50 Mgd Plant at 90% PF.

COST SUMMARY PAGE

CAPITAL COMPONENTS	COST-$/YR	COST-C/KGAL	COST-$DIRECT
CONDENSING SURFACE	1464860.89	8.9185	14984235.43
SHELL AND FOUNDATION	1405120.15	8.5548	14373140.28
PUMPS AND MOTORS	255457.81	1.5553	2613108.14
SEA-WATER INTAKE	183972.62	1.1201	1881877.72
VALVES AND PIPING	103660.72	0.6311	1060357.75
CHEMICAL CAPITAL	71631.90	0.4361	732731.20
INSTRUMENTS	75959.42	0.4625	776997.87
ELECTRICAL	25115.42	0.1529	256908.58
DEAERATOR	29189.81	0.1777	298585.99
BRINE HEATER	87340.82	0.5318	893419.64
SITE, BLDGS, CRANES	16003.93	0.0974	163706.07
STEAM PLANT	593461.19	3.6132	4489446.82
TOTAL CAPITAL	4162392.40	25.3418	42524515.49*
TOTAL INVESTMENT, $DIR+IND, INCLUDING N_2 SYSTEM			57573152.17
SPECIFIC INVESTMENT, $/GPD			1.15146
RETUBING		0.0	
OPERATING COMPONENTS			
HEAT	4102757.01	24.9787	
CHEMICALS	271026.19	1.6501	
POWER	579004.38	3.5251	
OPERATING	528724.19	3.2190	
MAINT. + SUPPLIES	357836.09	2.1786	
TOTAL OPERATING	5839347.86	35.5516	
TOTAL(CAP+RETUB+OP)	10001550	60.89	
COST FACTORS			
COST OF POWER,C/KWHR	0.480000		
COST OF HEAT,C/MMBTU	34.999996		
ANNUAL CHARGE RATE	0.072297		
INTEREST RATE	0.046250		
HIGHER COST FACTOR	1.352193		
PUMP AND MOTOR EFF.	0.827000		
PLANT LOAD FACTOR	0.900000		
PLANT LIFE,YEARS	30.000000		

	REJECT	RECOVERY	BRINE HEATER
TUBE LIFE,YEARS	30.000	30.000	30.000
AREA COST,$/SQ.FT.	2.859	2.859	2.859

*Nitrogen (N_2) System Not Included.

TABLE 4. Typical Cost and Design Values for an Optimized MSF Plant. (continued)

I	SUMMARY OF PLANT DATA	
	GENERAL	
	PLANT CAPACITY, MGD	50.0000
	PERFORMANCE RATIO	13.7487
	SEA WATER CONCENTRATION	0.0340
	PRODUCT CONCENTRATION, PPM	25.0000
	CONCENTRATION RATIO	2.0000
	NO OF REJECT STAGES	2.0000
	NO OF RECOVERY STAGES	28.0000
	YEAR CONSTRUCTION STARTED	1969.0000
	TEMPERATURES - DEG F	
	STEAM	258.0000
	MAXIMUM BRINE	250.0000
	BLOWDOWN	89.6265
	PRODUCT	84.9268
	OCEAN	61.0000
	FLOW RATES, MILLIONS OF LB/HR	
	STEAM	1.3377
	PRODUCT	17.2855
	BLOWDOWN	17.2728
	SEA INTAKE	49.2863
	HEAT REJECT	14.7280
	RECYCLE	88.4307
	RECOV. TUBING, BRINE HTR.	122.9889
	REJECT TUBING	49.2863
II	DESCRIPTION OF PHYSICAL PLANT	
	NO OF TRAINS	2.0000
	NO OF MODULES	8.0000
	NO OF LEVELS	1.0000
	PLANT HEIGHT, FT	12.9500
	RECOVERY LENGTH, FT	592.5948
	RECOVERY TRAIN WIDTH,FT	76.8681
	REJECT LENGTH, FT	83.6767
	REJECT TRAIN WIDTH, FT	66.7388
	TOTAL PLANT VOLUME, MILLIONS OF CUBIC FEET	1.3244

TABLE 4. Typical Cost and Design Values for an Optimized MSF Plant. (continued)

III TUBING PARAMETERS			
	REJECT	RECOVERY	BRINE HEATER
OUTSIDE DIAMETER, IN.	0.75000	0.75000	0.75000
WALL THICKNESS, IN.	0.04900	0.04900	0.04900
K,BTU/HR FT2 F	26.00000	26.00000	26.00000
FOULING RESISTANCE	0.00070	0.00050	0.00050
FLOODING FACTOR	19.00000	19.00000	19.00000
NO OF TUBES (THOUSANDS)	18.48500	45.55500	44.64900
TUBE LENGTH, FT	83.67672	592.59483	17.65260
AREA,THOUSANDS OF SQ FT	303.70850	5301.60981	154.75933
VELOCITY, FPS	5.00000	5.00000	5.35221
FRICTIONAL HEAD, FT	13.33666	94.44962	3.17186
OVERALL U, B/HR-FT2-F	419.24068	597.06560	644.83546
H INSIDE , B/HR-FT2-F	1128.60442	1720.58371	2266.55665
H OUTSIDE, B/HR-FT2-F	2027.33998	3035.31713	2666.90408
AVG LMTD, DEG F	11.74956	5.60768	12.59839
TEMPERATURE IN, DEG F	61.00000	89.62649	239.30900
TEMPERATURE OUT, DEG F	89.62649	239.30900	250.00000

IV PUMPING PARAMETERS			
	FLOW-GPM	HEAD-FT	POWER-MW
SEA-WATER DELIVERY	102679.77092	69.18666	1.55352
RECYCLE	256227.06146	211.31865	11.84056
BLOWDOWN	35984.95449	40.00000	0.31477
PRODUCT	36011.43349	107.15000	0.84380
DEAERATOR			0.74745
TOTAL			15.30010

TABLE 5

Summary of Cost for Optimized MSF Plants
As a Function of Size and Plant Load Factor

Plant Capacity, Mgd	25	25	25	25	25	25	50	50	50	50	50	50
Rated Plant Factor, %	10	20	30	50	70	90	10	20	30	50	70	90
Perf. Ratio, lb/1000 Btu	8.266	9.445	10.288	11.712	12.656	13.52	8.271	9.522	10.499	11.873	12.959	13.749
No. Stages, Heat Recovery	17	20	21	24	26	27	17	20	22	24	26	28
No. Stages, Heat Reject	2	2	2	2	2	2	2	2	2	2	2	2
No. Trains	2	2	2	2	2	2	2	2	2	2	2	2
Tot. Surface, 10^3 sq ft	1517	1747	1945	2272	2505	2753	3042	3536	3961	4642	5202	5604
Capital Cost, $												
Surface, Condensing	4,199,000	4,817,000	5,348,000	6,221,000	6,842,000	7,503,000	8,253,000	9,561,000	10,682,000	12,468,000	13,934,000	14,984,000
Shell & Foundations	3,732,000	4,462,000	4,962,000	5,987,000	6,748,000	7,473,000	7,005,000	8,434,000	9,633,000	11,392,000	13,006,000	14,373,000
Pumps & Motors	1,482,000	1,475,000	1,475,000	1,482,000	1,489,000	1,499,000	2,581,000	2,969,000	2,569,000	2,582,000	2,599,000	2,613,000
Seawater Intake	1,086,000	1,050,000	1,030,000	997,000	974,000	953,000	2,151,000	2,081,000	2,033,000	1,972,000	1,922,000	1,882,000
Brine Heater	615,000	569,000	543,000	505,000	485,000	468,000	1,182,000	1,089,000	1,031,000	964,000	920,000	893,000
Other Direct Costs	1,631,000	1,624,000	1,618,000	1,613,000	1,611,000	1,571,000	3,336,000	3,318,000	3,306,000	3,298,000	3,293,000	3,290,000
Indirect Costs	5,126,000	5,606,000	5,974,000	6,648,000	7,134,000	7,603,000	8,044,000	9,912,000	10,643,000	11,749,000	12,680,000	13,395,000
Subtotal, MSF	17,871,000	19,602,000	20,950,000	23,453,000	25,283,000	27,070,000	33,551,000	36,962,000	39,897,000	44,424,000	48,354,000	51,430,000
Boiler & N_2 System	5,267,000	4,716,000	4,395,000	3,949,000	3,704,000	3,508,000	9,369,000	8,334,000	7,683,000	6,937,000	6,451,000	6,143,000
Total Capital Cost	23,138,000	24,318,000	25,345,000	27,402,000	28,987,000	30,578,000	42,920,000	45,296,000	47,580,000	51,361,000	54,805,000	57,573,000
Water Cost, $/yr												
Fixed Charges	1,673,000	1,758,000	1,832,000	1,981,000	2,096,000	2,211,000	3,103,000	3,275,000	3,440,000	3,713,000	3,962,000	4,162,000
Heat	379,000	664,000	914,000	1,338,000	1,733,000	2,086,000	758,000	1,316,000	1,791,000	2,639,000	3,385,000	4,103,000
Chemicals	29,000	58,000	86,000	144,000	201,000	259,000	30,000	60,000	90,000	151,000	211,000	271,000
Power	29,000	58,000	89,000	152,000	218,000	288,000	58,000	117,000	178,000	306,000	441,000	579,000
Operating	99,000	137,000	175,000	252,000	329,000	403,000	131,000	183,000	230,000	330,000	429,000	529,000
Maint. & Supplies	30,000	47,000	65,000	104,000	146,000	191,000	56,000	87,000	121,000	194,000	274,000	358,000
Total Water Cost	2,239,000	2,722,000	3,161,000	3,971,000	4,723,000	543,800	4,136,000	5,038,000	5,850,000	7,333,000	8,702,000	10,002,000
Cost Per Startup Cycle	23,000	23,000	23,000	23,000	23,000	23,000	38,000	38,000	38,000	38,000	38,000	38,000

Plant Capacity, Mgd	75	75	75	75	75	75	100	100	100	100	100	100
Rated Plant Factor, %	10	20	30	50	70	90	10	20	30	50	70	90
Perf. Ratio, lb/1000 Btu	8.310	9.603	10.579	12.083	13.073	13.856	8.314	9.630	10.619	12.136	13.191	13.881
No. Stages, Heat Recovery	18	20	22	25	27	28	18	20	22	25	27	28
No. Stages, Heat Reject	2	2	2	2	2	2	2	2	2	2	2	2
No. Trains	2	2	2	2	2	2	2	2	2	2	2	2
Tot. Surface, 10^3 sq ft	4534	5367	6008	7075	7833	8515	6051	7186	8057	9498	10595	11388
Capital Cost, $												
Surface, Condensing	12,178,000	14,356,000	16,029,000	18,801,000	20,764,000	22,528,000	16,131,000	19,080,000	21,335,000	25,056,000	27,877,000	29,913,000
Shell & Foundations	10,336,000	12,297,000	14,038,000	17,016,000	19,219,000	20,966,000	13,441,000	16,026,000	18,313,000	22,214,000	25,241,000	27,281,000
Pumps & Motors	3,570,000	3,553,000	3,554,000	3,573,000	3,594,000	3,618,000	4,494,000	4,473,000	4,474,000	4,499,000	4,529,000	4,555,000
Seawater Intake	3,199,000	3,107,000	3,029,000	2,930,000	2,861,000	2,805,000	4,248,000	4,124,000	4,020,000	3,889,000	3,788,000	3,727,000
Brine Heater	1,728,000	1,589,000	1,506,000	1,399,000	1,344,000	1,306,000	2,267,000	2,083,000	1,972,000	1,833,000	1,754,000	1,713,000
Other Direct Costs	4,724,000	4,695,000	4,678,000	4,662,000	4,654,000	4,652,000	6,059,000	6,015,000	5,993,000	5,970,000	5,958,000	5,954,000
Indirect Costs	12,339,000	13,542,000	14,517,000	16,133,000	17,280,000	18,233,000	15,276,000	16,794,000	18,021,000	20,054,000	21,593,000	22,699,000
Subtotal, MSF	48,074,000	53,139,000	57,351,000	64,514,000	69,718,000	74,108,000	61,916,000	68,595,000	74,128,000	83,515,000	90,741,000	95,842,000
Boiler & N_2 System	13,092,000	11,606,000	10,707,000	9,586,000	8,978,000	8,554,000	16,643,000	14,723,000	13,570,000	12,141,000	11,327,000	10,857,000
Total Capital Cost	61,166,000	64,745,000	68,058,000	74,100,000	78,696,000	82,662,000	78,559,000	83,318,000	87,698,000	95,656,000	102,068,000	106,699,000
Water Cost, $/yr												
Fixed Charges	4,422,000	4,681,000	4,920,000	5,357,000	5,689,000	5,976,000	5,680,000	6,024,000	6,340,000	6,916,000	7,378,000	7,714,000
Heat	1,131,000	1,958,000	2,666,000	3,890,000	5,034,000	6,106,000	1,508,000	2,603,000	3,541,000	5,164,000	6,652,000	8,127,000
Chemicals	43,000	87,000	130,000	216,000	302,000	389,000	56,000	113,000	169,000	281,000	393,000	506,000
Power	87,000	176,000	268,000	461,000	662,000	872,000	116,000	235,000	358,000	616,000	887,000	1,164,000
Operating	149,000	209,000	267,000	385,000	504,000	620,000	172,000	237,000	304,000	434,000	563,000	693,000
Maint. & Supplies	79,000	123,000	172,000	278,000	391,000	512,000	101,000	158,000	220,000	358,000	506,000	660,000
Total Water Cost	5,911,000	7,234,000	8,423,000	10,587,000	12,582,000	14,475,000	7,633,000	9,370,000	10,932,000	13,769,000	16,379,000	18,864,000
Cost Per Startup Cycle	64,000	64,000	64,000	64,000	64,000	64,000	77,000	77,000	77,000	77,000	77,000	77,000

TABLE 6

Unit Cost of Water as a Function of the Operating Plant Load Factor and Optimum Load Factor

Plant Size 25 Mgd

Operating Load Factor	Total unit water cost and cost of fuel ¢/1000 gal. for the plant that is optimized at the given plant load factor											
	10%		20%		30%		50%		70%		90%	
	Total	Fuel	Total	Fuel	Total	Fuel	Total	Fuel	Total	Fuel	Total	Fuel
10%	247.9	41.5	252.3	36.2	258.0	33.2	267.6	29.2	282.2	26.9	291.9	25.4
20%	150.7	41.5	150.4	36.4	151.7	33.2	156.1	29.2	160.9	26.9	163.3	25.4
30%	118.4	41.5	116.4	36.2	116.3	33.4	118.1	29.2	120.5	26.9	122.9	25.4
50%	92.5	41.5	89.3	36.2	88.0	33.2	87.0	29.3	88.2	26.9	89.1	25.4
70%	81.4	41.5	77.6	36.2	75.8	33.2	74.5	29.2	74.3	27.1	74.6	25.4
90%	75.0	41.5	70.9	36.2	68.9	33.2	67.0	29.2	66.4	26.9	66.2	25.4

TABLE 7

Unit Cost of Water as a Function of the Operating Plant Load Factor and Optimum Load Factor

Plant Size 50 Mgd

Operating Load Factor	Total unit water cost and cost of fuel ¢/1000 gal. for the plant that is optimized at the given plant load factor											
	10%		20%		30%		50%		70%		90%	
	Total	Fuel	Total	Fuel	Total	Fuel	Total	Fuel	Total	Fuel	Total	Fuel
10%	228.7	41.5	232.8	36.0	238.9	32.6	250.7	28.8	262.0	26.4	271.4	25.0
20%	139.6	41.3	139.1	36.1	140.5	32.6	144.5	28.8	149.1	26.4	153.2	25.0
30%	109.8	41.3	107.7	36.0	107.5	32.7	109.1	28.8	111.4	26.4	112.7	25.0
50%	86.0	41.3	82.7	36.0	81.3	32.6	80.8	28.9	81.3	26.4	82.1	25.0
70%	75.8	41.3	71.8	36.0	70.0	32.6	68.6	28.8	68.4	26.5	68.1	25.0
90%	69.9	41.3	65.7	36.0	63.5	32.6	61.6	28.8	61.0	26.4	60.9	25.0

TABLE 8

Unit Cost of Water as a Function of the Operating Plant Load Factor and Optimum Load Factor

Plant Size 75 Mgd

Operating Load Factor	Total unit water cost and cost of fuel ¢/1000 gal. for the plant that is optimized at the given plant load factor											
	10%		20%		30%		50%		70%		90%	
	Total	Fuel	Total	Fuel	Total	Fuel	Total	Fuel	Total	Fuel	Total	Fuel
10%	218.3	41.3	222.5	35.6	228.3	32.3	240.7	28.3	250.8	26.2	259.7	24.8
20%	133.9	41.2	133.3	35.8	134.5	32.3	138.9	28.3	143.0	26.2	146.8	24.8
30%	105.8	41.2	103.5	35.6	103.3	32.3	105	28.3	107.1	26.2	109.1	24.8
50%	83.3	41.2	79.7	35.6	78.4	32.3	77.8	28.4	78.2	26.2	79.1	24.8
70%	73.7	41.2	69.6	35.6	67.6	32.3	66.9	28.3	66.0	26.3	66.1	24.8
90%	68.1	41.2	63.7	35.6	61.5	32.3	59.5	28.3	58.9	26.2	58.8	24.8

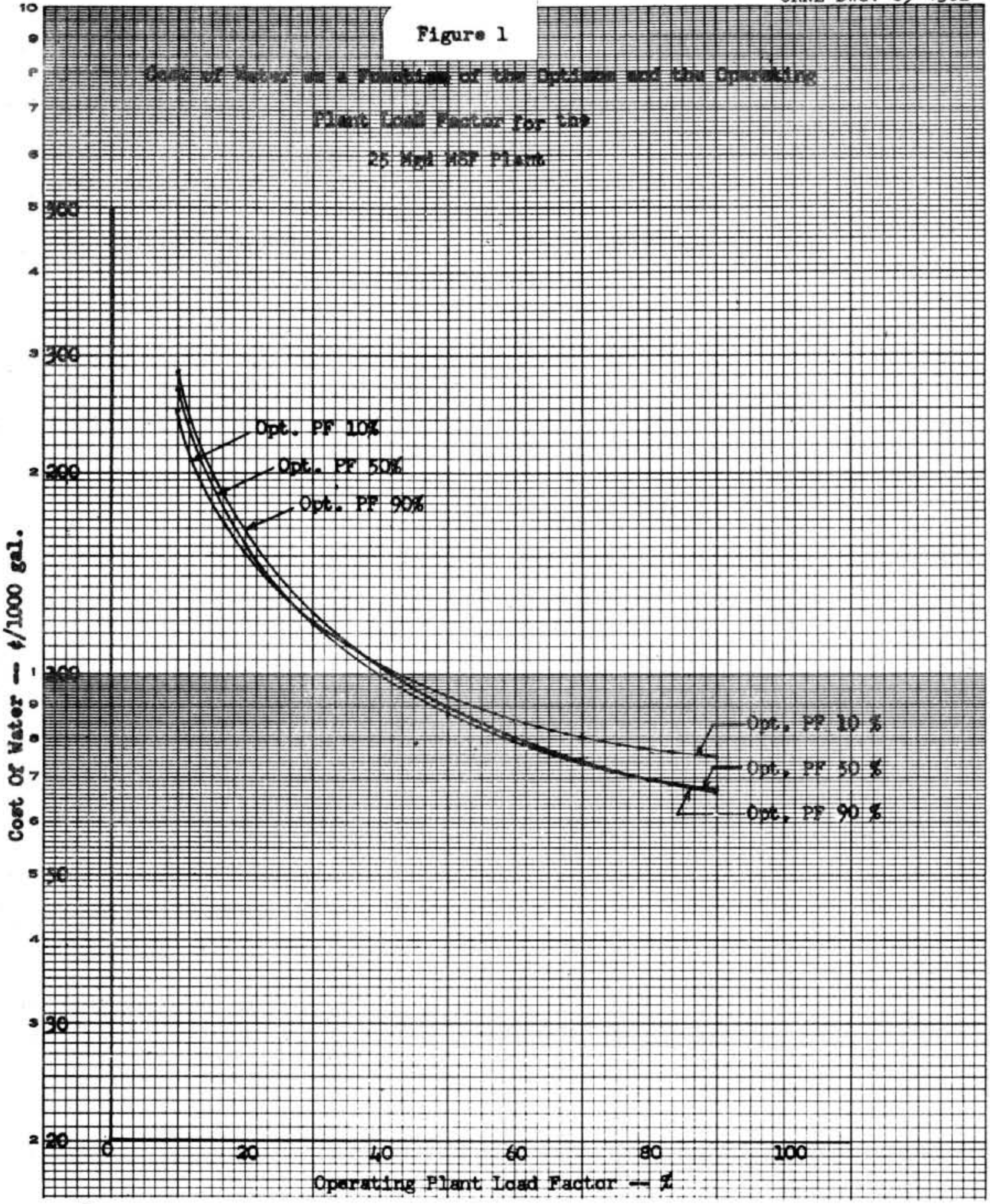
TABLE 9

Unit Cost of Water as a Function of the Operating Plant Load Factor and Optimum Load Factor

Plant Size 100 Mgd

Operating Load Factor	Total unit water cost and cost of fuel ¢/1000 gal. for the plant that is optimized at the given plant load factor											
	10%		20%		30%		50%		70%		90%	
	Total	Fuel	Total	Fuel	Total	Fuel	Total	Fuel	Total	Fuel	Total	Fuel
10%	211.2	41.3	215.3	35.5	221.0	32.2	233.2	28.2	242.9	26.1	251.6	24.7
20%	130.2	41.2	129.4	35.7	130.6	32.2	134.9	28.2	138.8	26.1	142.5	24.7
30%	103.1	41.2	100.8	35.5	100.5	32.3	102.1	28.2	103.9	26.1	106.2	24.7
50%	81.5	41.2	77.9	35.5	76.4	32.2	75.9	28.3	76.3	26.1	76.9	24.7
70%	72.3	41.2	68.1	35.5	66.1	32.2	64.6	28.2	64.4	26.0	64.6	24.7
90%	69.9	41.2	62.4	35.5	60.1	32.2	58.1	28.2	57.6	26.1	57.4	24.7

ORNL DWG. 69-4302



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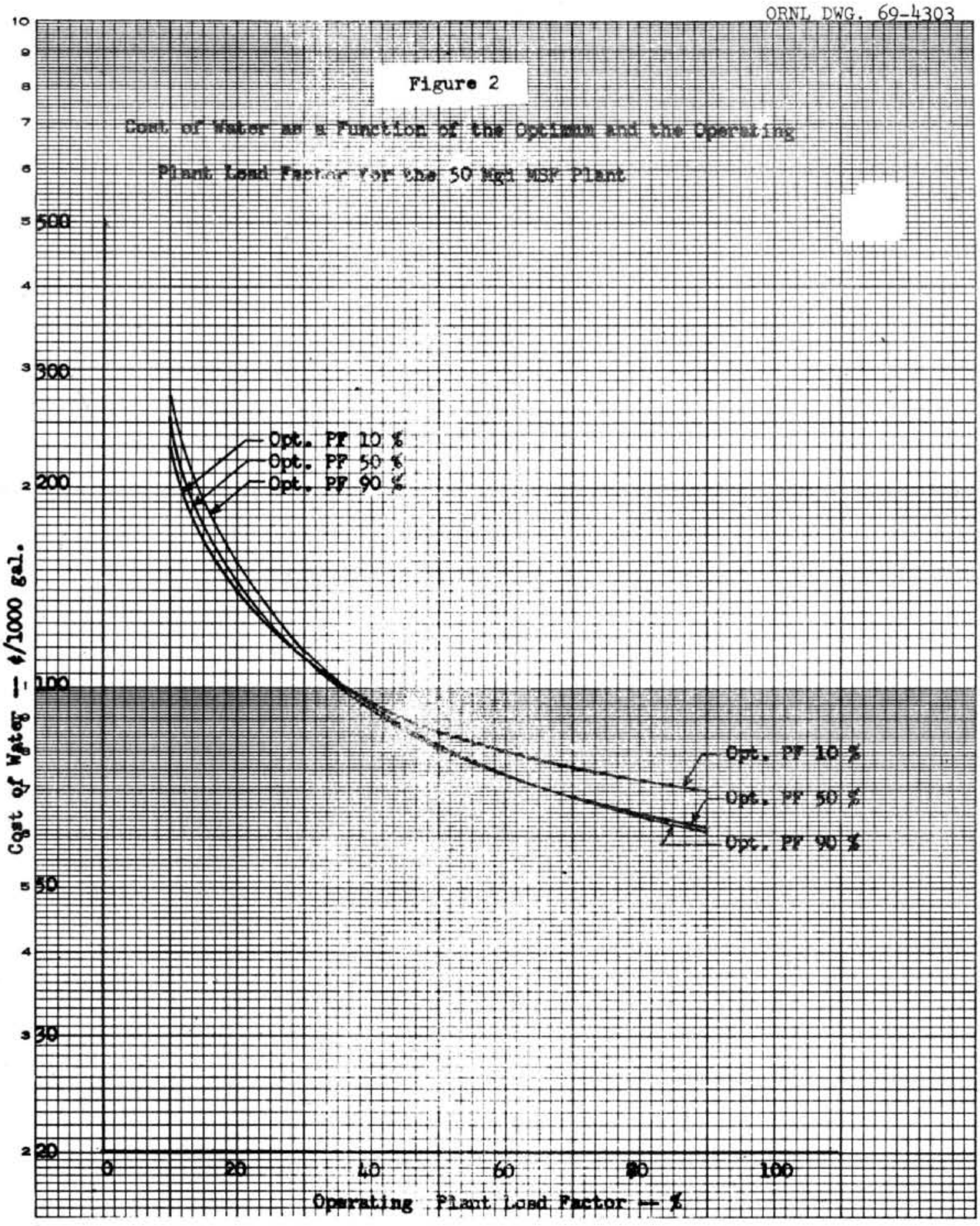

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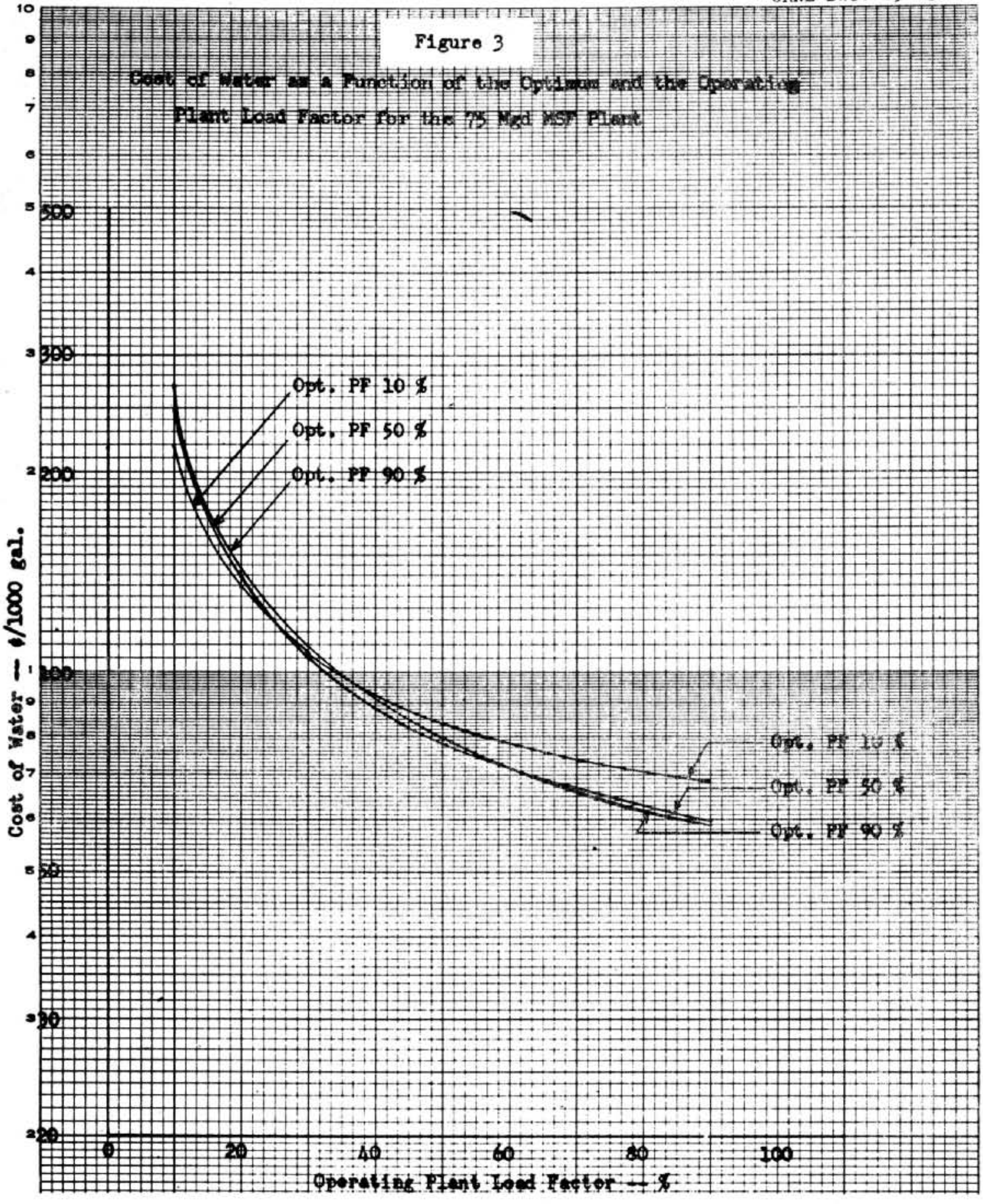

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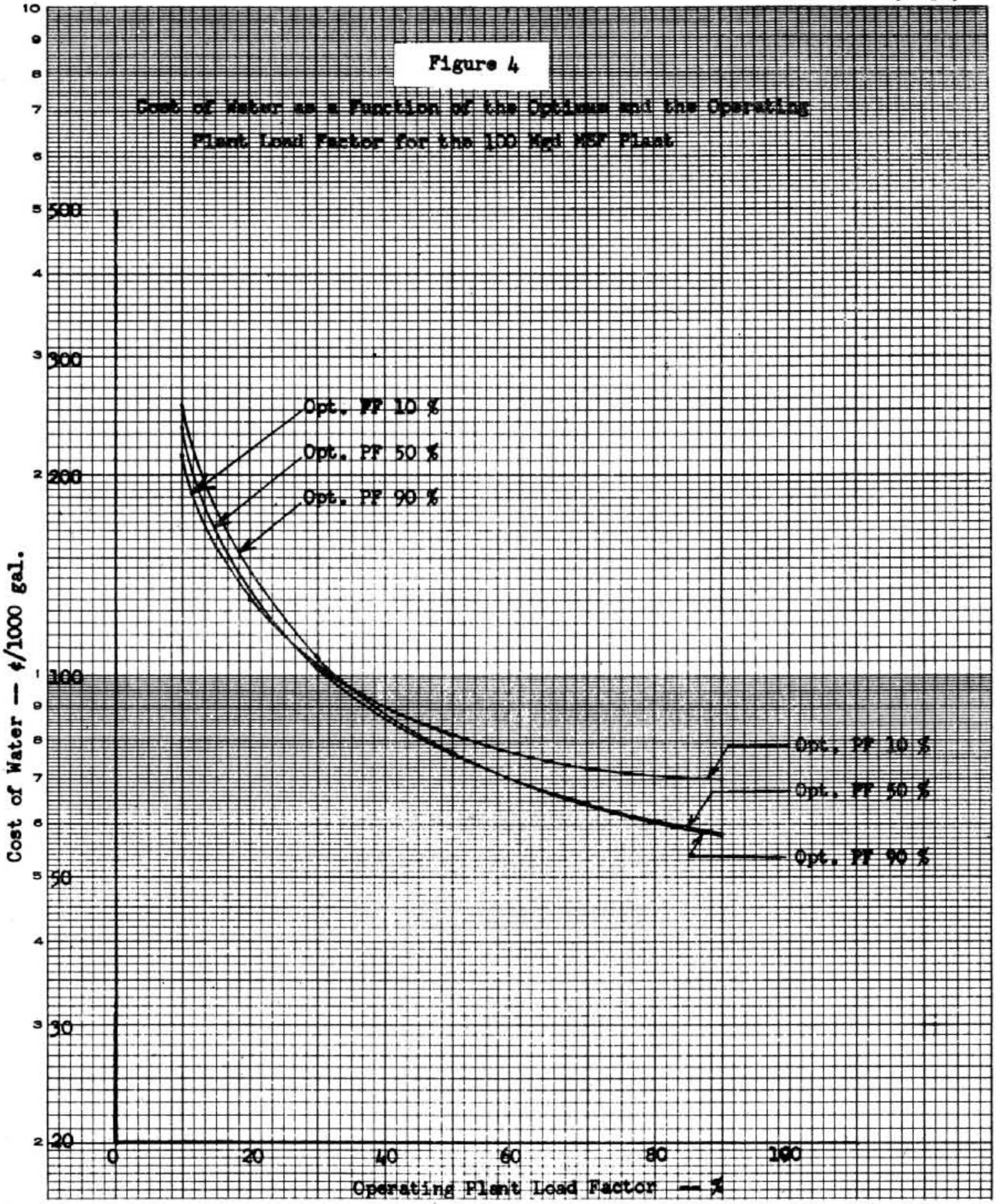

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April 29, 1969

Mr. Wesley H. Blood
Utah State University
College of Engineering
Logan, Utah 84321

Dear Mr. Blood:

SUBJECT: Reply to Your Letter of April 22, 1969

Time does not permit us to develop cost tables for 150, 200, 250 and 300 Mgd plants as requested. I would suggest that the 100 Mgd costs be used as a base with the following arithmetic multipliers for unit capital, annual or water costs:

100 Mgd	1.0
150 Mgd	0.97
200 Mgd	0.94
250 Mgd	0.92
300 Mgd	0.90

The total annual cost ($/yr) at 0% plant factor would be the sum of the annual fixed charge tabulated in my letter to Mr. Clyde, March 14, 1969, plus the following operating cost:

Plant Size	Op. Cost, $/yr
25 Mgd	20,740
50 Mgd	30,480
75 Mgd	31,420
100 Mgd	42,260

It is likely that a thorougn analysis of the questions would give more refined answers in both cases. I have reviewed our approach briefly with Shiozawa and I believe he is in agreement with the approach taken.

Sincerely,

I. Spiewak

IS:jb
cc: Dr. C. G. Clyde
Mr. Sam Shiozawa

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