A MATHEMATICAL MODEL FOR EVALUATING THE POTENTIAL OF DESALTING[1]

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ABSTRACT. The Office of Saline Water, which has federal responsibility for developing low-cost, saline sources of fresh water, has recognized the need for an improved method of forecasting the future potential of desalting in this country. The magnitude of the role of desalting will influence the plans of federal, state, and local water resource agencies and the research and development programs of manufacturers. A dynamic simulation model has been developed by Arthur D. Little, Inc. under contract by OSW to translate relevant factors of water supply and demand into a forecast of desalting potential. The model projects the needs for desalting in 20 hydrologic regions of the U.S. Model performance has thus far been demonstrated by the development of a forecast and a battery of related sensitivity tests. Current results indicate the following potential desalting capacities: 225 MGD in 1980; 2,250 MGD in 2000; and 7,000 MGD in 2020. Significant improvements in desalting economics promise to increase these potentials by a factor of four or five by 2000-2020. Model inputs and results are continuing to be refined. When completed, OSW will have a dynamic tool with which to guide its **R&D** program.
(KEY WORDS: computer model; desalting; desalting costs; forecasting; simulation; water costs; water requirements; water supply)

INTRODUCTION

In 1952, Congress established the Office of Saline Water (OSW) with the mandate to research and develop low-cost processes to convert saline water[3] into fresh water. The wisdom of that legislation is now being proven as the demands of population growth and a consuming economy place ever heavier burdens on our water supply and quality.

The cost of seawater conversion has been reduced from $8/1,000 gallons (1970 dollars), when the program began, to a cost for in-service plants of about 80¢/1,000 gallons. Moreover, technology for larger-scale and lower cost distillation processes is now proven. At the same time, membrane processes can now produce fresh water from a moderately saline source for about 40¢/1,000 gallons.

As past R&D by OSW was guided by the broad need for technology to produce a low-cost source of water supply, so future R&D must be guided by more specific requirements of potential desalting applications. An evaluation of the future role of desalting requires, among other things, a judgment of the magnitude of future desalting capacity. Typically, such a forecast would be developed from either an intuitive or statistical extrapolation of past history. Desalting, however, has had only a limited and recent history as a water supply resource in the United States. In order to forecast its potential, therefore, OSW has needed a system which will relate desalting's potential to the important conditions and considerations which will determine its use.

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[2]Respectively, Arthur D. Little, Inc., Cambridge, Massachusetts; and Office of Saline Water.
[3]Saline water includes sea water, brackish water, or other mineralized or chemically charged water.

PRESENT DESALTING USE

Existing U.S. desalting capacity is comprised of about 48 million gallons per day (MGD) in 312 plants, but only 20 plants representing 9 MGD capacity produce water for municipal purposes. These are mostly in small communities, relatively isolated from sources of conventional water supplies. Coalinga in California, whose alternative to desalting was rail-transported water, or Key West, Florida, whose alternative was a long undependable pipe line to a mainland source, are not atypical examples. In the future, however, desalting for isolated small communities will represent a much smaller part of the potential.

Because desalting has filled only limited and specialized requirements thus far, it is hazardous to venture projections of future U.S. applications beyond a few years. But at the same time, the desirability of anticipating the future is clear from OSW's standpoint. OSW wants to maximize the dollars spent on its R&D program, and to have that program properly oriented to best fill real-world needs. In particular, given current projections of national water requirements, OSW believes that desalting will in fact be called on to help maintain the water supply/demand balance.

FUTURE DESALTING APPLICATIONS

Future applications of desalting are expected to develop from the needs of (1) regional water supply systems for augmentation of conventional sources in critical water years; (2) arid portions of the Pacific Southwest in lieu of large-scale interbasin transfers of conventional supplies; (3) water quality improvement; (4) isolated communities for augmentation of water supply; and (5) highly water-efficient agriculture, for growing specialty crops in climatically favorable areas.

Valuable guidance to OSW's program would result if these future applications could be related to both short and long time frames, to the mix of desalting processes, and to the range of desalting plant sizes. The need for this detail must, of course, be viewed against the range of uncertainties under which projections of desalting use must be made.

WATER SUPPLY AND DEMAND UNCERTAINTIES

Uncertainties are introduced in the planning for water supply by the number of political, legal, and economic considerations that must be considered.

1. The elasticity of demand for water quantity and quality has never been fully defined. How much are people willing to pay for high quality water? How will metering affect their habits of water use? How will increasing affluence affect these habits and their willingness to pay? Can the economics of recycling by industry be reasonably estimated; i.e., the price of water at which recycling by industry will become attractive? Are legal restraints and institutional inertias built permanently into the water supply system?

The demand for water remains to be correlated to the price of water. As long as this price elasticity remains unknown, the level of confidence is lessened in projected demands and therefore projected needs for augmentation of water supply.

2. The relative economics of alternative sources of water supply is difficult to assess. It is well known that the cost of conventional water supply is increasing, inflation factors aside, as the better reservoir sites are used up and land becomes more expensive. Also, the firm yield of the last-added reservoir in a system will probably be less, in relation to its total capacity. Moreover, tapping new sources of surface water supply usually means going farther from user points, with consequent increasing conveyance costs.

Planners are faced with the difficult task of developing cost estimates for new conventional sources in the first instance, and then relating these costs to firm yield. Nevertheless, the analysis of desalting's potential requires an evaluation of the cost of these alternatives in order to properly assess the role of desalting.

3. Conventional water sources may no longer be readily transferred across political boundaries. The possibility of developing Pacific Northwest water sources for use in the Southwest is the best known example, although diversion projects are relevant in many parts of the country. The needs for these diversions must, of course, be balanced against the considerable claims of areas of origin. Obviously, this balance is not easily quantified, yet the impact on water supplies may be critical. In fact, this one parameter may, in some areas, be decisive in describing future water supply alternatives and the role that desalting might play.

4. Desalting technology for large plants is not fully developed. Gains may result from refinements of existing technology, from economies of scale, from reduced energy costs, and from new process techniques or significant advances in existing ones, i.e., reverse osmosis. The future cost of desalted water, therefore, can be projected only with an envelope of confidence.

MODELING DESALTING'S FUTURE

An analysis of desalting potential, in view of the variables and uncertainties mentioned above, seemed to OSW to be best approached through the medium of a mathematical model. Modeling does not attempt to entirely reproduce the real world, but only to incorporate those parameters essential to decision making, under a range of choices. Moreover, once a model has been created and its logic tested, it may then be used to evaluate the impact of a range of different assumptions.

For instance, in the realm of "What if":

1. the cost of desalted water is reduced at various rates of acceleration?
2. the cost of desalted water at some future date is less than is now anticipated?
3. quality standards are enforced on interstate streams? for municipal water supplies?
4. there are drastic changes in requirements for water augmentation in a particular hydrologic region?
5. there are significant changes in birth rates and population growth?

It is anticipated that the model will be regularly exercised to provide answers to these types of assumptions, to update forecasts as future water supply and demand data are improved, and to determine the effects of changes in cost trends in desalting and conventional water supplies.

Thus the model becomes a valuable tool to aid OSW in viewing the potential for desalting and in guiding R&D efforts to improve processes and lower costs. Also, a projection of the role of desalting will provide inputs for the planning programs of federal, state, and local water resource agencies and give insights to manufacturers with which to direct their R&D and investment decisions.

FORECASTING BY SIMULATION

Mathematical models are finding increased use in the management of our water resources. Noteworthy in this respect has been the widespread use of models of river basins and regional hydrologies. Models have also become more common in the simulation of decision environments.

Simulation models to forecast economic or market events have found increased acceptance

(1) as computer and management science techniques have progressed; (2) as statistical forecasting models have failed to produce needed insights into uncertain futures; and (3) as the value of intelligent forecasts has become necessary for effective planning.

In fields of emerging technologies such as desalting, the history of application in the U.S. is too limited for useful forecasting to result from statistical techniques like regression analysis or exponential smoothing. If anything is to be discovered about the magnitude of desalting's potential, it must be developed from an analysis of anticipated conditions and the factors which will determine the need for desalting.

A dynamic simulation model has been developed by Arthur D. Little, Inc. under contract by OSW to translate the determinants of water demand and supply into a forecast of desalting potential. The basic premise of this approach is that the major challenge of forecasting is one of anticipating the future with the benefit of both current information and experienced insight. Specifically, the function of the model is to mobilize available information into a more rigorous, complete, and effective framework for viewing the future of desalting. The model is built to incorporate the experience of the OSW and information from other agencies into a system which realistically models the structure of water management in the U.S. and simulates future water supply decisions under a range of possible conditions.

MODEL DIMENSIONS

This mathematical model is designed to project the needs for desalting in the 20 hydrologic regions of the United States used by the Water Resources Council in the National Water Assessment. These regional projections, in turn, are based on the balance of water supply and demand in 100 subregions. Projections are made in five-year intervals between 1965 and 2020. The model is built to utilize data similar to that provided by the National Water Assessment. It considers the water supply needs of four major water using sectors of the economy: agricultural, industrial, municipal, and power.

The projection model has been programmed in FORTRAN IV, a general-purpose computer language for scientific and management problems. The model was developed for the IBM 360, Model 65 computer system and is in operation on the IBM 360 facilities operated by the U.S. Geological Survey in Washington, D.C. The FORTRAN program consists of eight subroutines. These include a MAIN routine to call the other routines, an input routine, three output routines, and three operating routines. Together the subroutines consist of 1,500 FORTRAN statements. The data used by the program presently occupies about 500 cards and encompasses more than 30 types of inputs. Computer storage required by the model amounts to less than 200 K bytes. Individual runs take two to three minutes of computer time.

MODEL SECTOR

The major relationships between the three operating modules and the other auxiliary modules in the complete computer program are indicated by the general flow diagram in Figure 1. Model operation begins with the reading of input data by the Input Module. The function of this input routine is to process the input data into a form required by the three operating modules. Thus, as indicated in Figure 1, withdrawal and consumption data are supplied to the Demand Module, stream quality vis a vis stream quality standards are provided to the Requirements Module, and water supply and cost data are provided for the Supply Module. In each case, other data are supplied in addition to these major items.

With each of these operating modules is associated an output routine which tabulates the

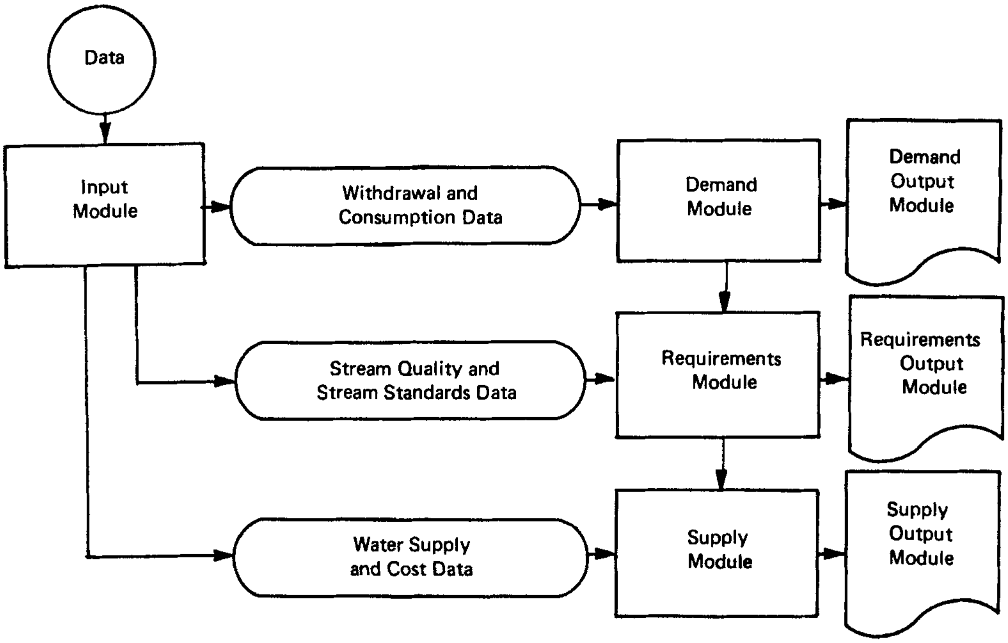

Fig. 1. General flow diagram of desalting potential model.

results of the operating module. The Demand Output Module produces a tabulation, by subregion, of five-year withdrawal and consumption projections. The Requirements Output Module prints out a similar summary of water requirements projections. The Supply Output Module converts the results of the Supply Module into a series of national, regional, and subregional summary tables.

DEMAND

The Demand Module interpolates the 20-year projections of the National Water Assessment or similar data into five-year projections. Flexibility in amending the assumptions underlying the Assessment projections is provided. The first of these assumptions is the number of consuming units in each consuming sector. These assumptions include the growths of population in the municipal sector, personal income in the industrial sector, kilowatt production in the power sector, and irrigated acreage in the agricultural sector.

A second assumption underlying the withdrawal projections are indices of water usage per consuming unit. These include gallons per capita per day (gcpd) in the municipal sector, gallons per unit of production in the industrial sector, gallons per kilowatt hour in the power sector, and gallons per irrigated acre in the agricultural sector. A final assumption of withdrawal projections is the extent of recycle practices.

The first two assumptions underlying consumption projections are identical to those of withdrawal: consuming unit growth and usage per unit growth. The third assumption is different and is the amount of water consumed per unit of total water usage.

REQUIREMENTS

In this study to project the needs for desalting, the primary mechanism for simulating the conditions of need is the balancing of water supply and demand. For the purposes of determining this balance, withdrawals are considered an overstatement of water demand since the return flows are subject to reuse. On the other hand, consumption (depletion) probably understates water demand insofar as it does not account for the quality deterioration of receiving streams. In this study, water demand has been divided into two parts: consumption requirements and dilution requirements. The dilution quantity is the water needed to dilute the amount of pollution in the watercourse and to maintain minimum stream flow at a desired level of water quality.

In the model, total water requirements are now calculated by the following equation:

$$R = C + (W\text{-}C)\,\frac{TDSE}{TDSS}$$

where: R = Requirements
C = Consumption
W = Withdrawal
TDSE = Quality of effluent, total dissolved solids (tds)
TDSS = Stream quality standards, tds, and
W-C = Return flow
$(W\text{-}C)\,\frac{TDSE}{TDSS}$ = Dilution requirements

This conceptual model is a steady-state system which (1) withdraws "W," (2) consumes "C," and (3) returns "W-C." To the consumption requirement is added the dilution requirement—the product of the return flow and the ratio of effluent quality to stream quality standards. Although this equation improves upon simple withdrawal or consumption concepts as a measure of true water requirements, it has not yet been completely developed. It will be reformulated as possible and necessary improvements become apparent.

SUPPLY

The need for augmenting natural supply is determined subregionally by a comparison of growing water demands to existing water supplies. Existing (available) supplies include both naturally "dependable" flows and man-made capacities for augmented supply. "Dependable" flow is defined as the annual level of stream flow which has been exceeded in 95% of the years of record. Man-made systems for storage and stream flow regulation provide the means for increasing dependable flows closer to average annual flow levels.

Although the balance of supply and demand are determined on a subregional basis, even the subregion represents a gross generalization of some local imbalances in supply and demand. In those subregions where local conditions vary widely—even in the face of an overall subregional surplus of natural supply—the model has the flexibility to account for special augmentation needs. Thus, a "local conditions adjustment" simulates these needs of a subregion for augmentation capacity.

The needs for augmentation are developed in five-year intervals, for each of 100 subregions, by type of consuming sector, and for selected plant size categories. The plant size categories used are:

1. Less than 1 MGD
2. 1 to 10 MGD
3. 10 to 50 MGD
4. Greater than 50 MGD

The program then surveys the possibilities of supplying these subregional needs from alternative sources. Six water supply alternatives are typically considered:

Conventional Alternatives	Desalting Alternatives
1. Reservoir Management	1. Sea Water
2. Importation	2. Brackish Water
3. Reuse	3. Recycle

COSTS

The costs of conventional water supply alternatives include costs at the water sources, for transportation, and for treatment. Source costs include those associated with a dam and reservoir. Transportation costs include pumping, pipeline and right-of-way. Treatment costs include those of sedimentation and filtration. Information on conventional water supply costs has been gleaned from published reports of the Bureau of Reclamation, the Texas Water Development Board, the American Water Works Association, the U.S. Geological Survey, and the Federal Water Quality Administration.

Estimates and projections of the costs of desalting were developed from the experience of existing installations, manufacturers' literature, and OSW feasibility studies. The costs of desalting which have been used in the model are generally those illustrated in Figure 2. Current cost estimates are based on the existing plant experience and results of specific OSW feasibility studies. The future costs indicated in the lower curves reflect prevailing OSW views on probable gains in desalting technology and economics.

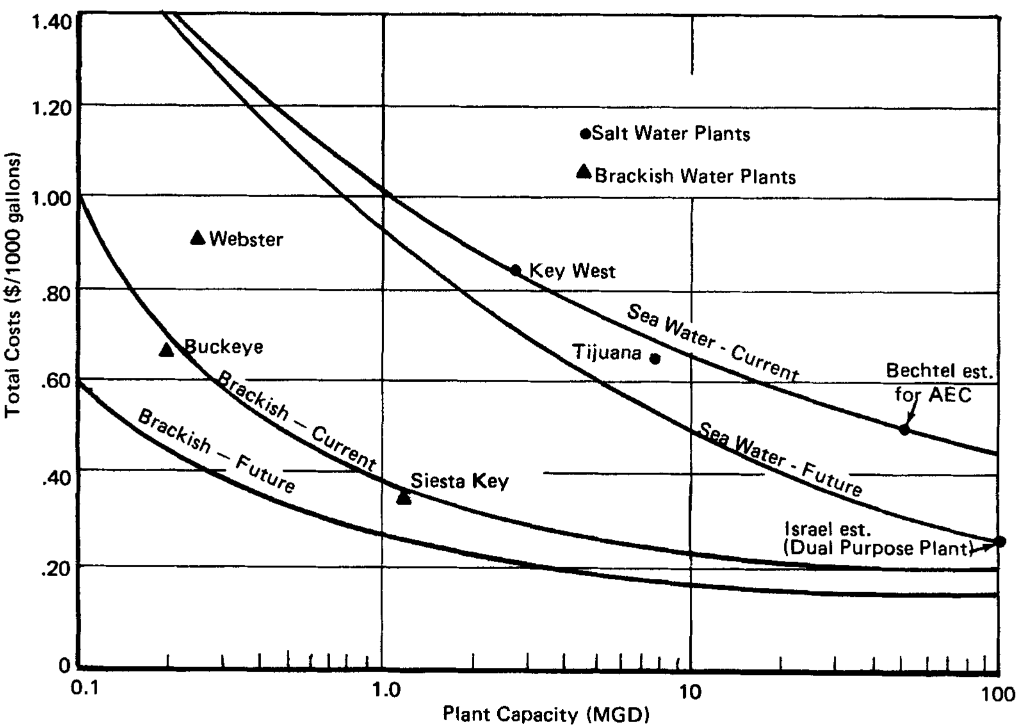

Fig. 2. Costs of desalted water.

The comparison of the costs of alternative water supplies is based on the calculation of annualized costs from the inputs of capital and operating costs for each alternative. Annualization places each of the calculated cost alternatives on an equivalent basis. Two factors affect the cost calculations over the forecasting period. The first factor is the effect that new technology or engineering advances will have upon the reduction of the cost of water supply from some of the alternatives. The alternatives which are expected to be most affected by the technological changes are the desalting and recycling alternatives. A second factor influencing the cost calculation is the effect that inflation will have upon increasing the cost of all alternatives.

After annualized cost have been calculated for each possible alternative, the program selects the minimum cost alternative. All of the requirements for added capacity, however, are not allocated necessarily to this minimum cost alternative. If other sources are sufficiently competitive (cost-wise) to the minimum cost alternative, then other supply (as many as two) alternatives may share in meeting the capacity requirement. This capacity share mechanism allocates the largest share to the minimum cost alternative and allocates smaller shares to the one or two competing alternatives.

PRELIMINARY RESULTS

A Base Run

A preliminary forecast (Base Run) of desalting potential has been developed on the basis of ongoing OSW feasibility studies, drafts of the Pacific Southwest Framework Studies, and the costs of desalting displayed in Figure 2. Seawater costs reflect the potentials of multistage flash (MSF) and vertical tube (VTE) distillation systems. Current brackish costs reflect the current economics of electrodialysis (ED), while future brackish costs are based more on the expected potential of reverse osmosis (R-O).

Figure 3 illustrates the projection of desalting potential developed from the Base Run. Potentials begin at 43 MGD in 1969, increase to 225 MGD in 1980, to 2,250 MGD in 2000, and to 7,000 MGD in 2020. These projections correspond to average annual growth rates in capacity of 16%/year between 1969 and 1980, 12%/year from 1980 to 2000, and 6%/year from 2000 to 2020.

Test Run 1. Accelerated Desalting Technology

A major criterion in judging the performance of the model was whether the model behaved in a manner which would be expected when some conditions were changed as they might in the real world. Two sensitivity tests involved changes in the future costs of desalting seawater. In the initial Base Run, the route by which desalting costs from seawater and brackish sources decline to their eventual level in 2020 is indicated by the upper curve of Figure 4. In that curve, the seawater desalting cost of 50¢ (for the largest plant size) in 1965 declines to 25¢ (in uninflated 1965 dollars) in 2020. In the first test run, we changed the decline of desalting costs from that of the upper curve to that of curve No. 1 in Figure 4.

By 1980, the cumulative installed capacity in Test Run 1 was nearly three times that in the Base Run. By 2000, capacity in the test run was nearly double that of the Base Run. Finally, since the curve in Figure 4 for Test Run 1 closely paralleled the curve in the Base Run in the 2000-2020 period, substantial differences in incremental additions in that period were not too different.

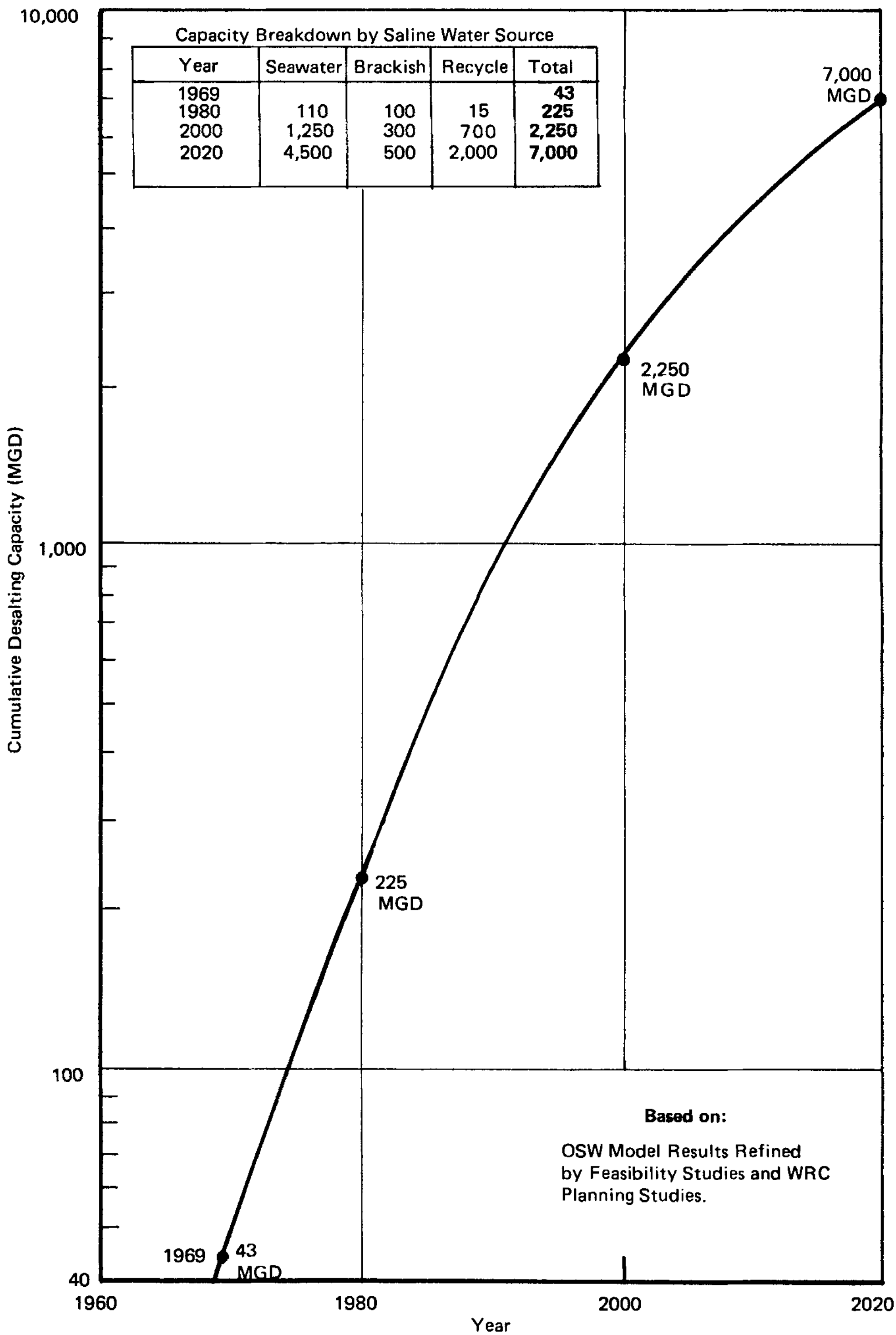

Fig. 3. Projected desalting potential in the United States.

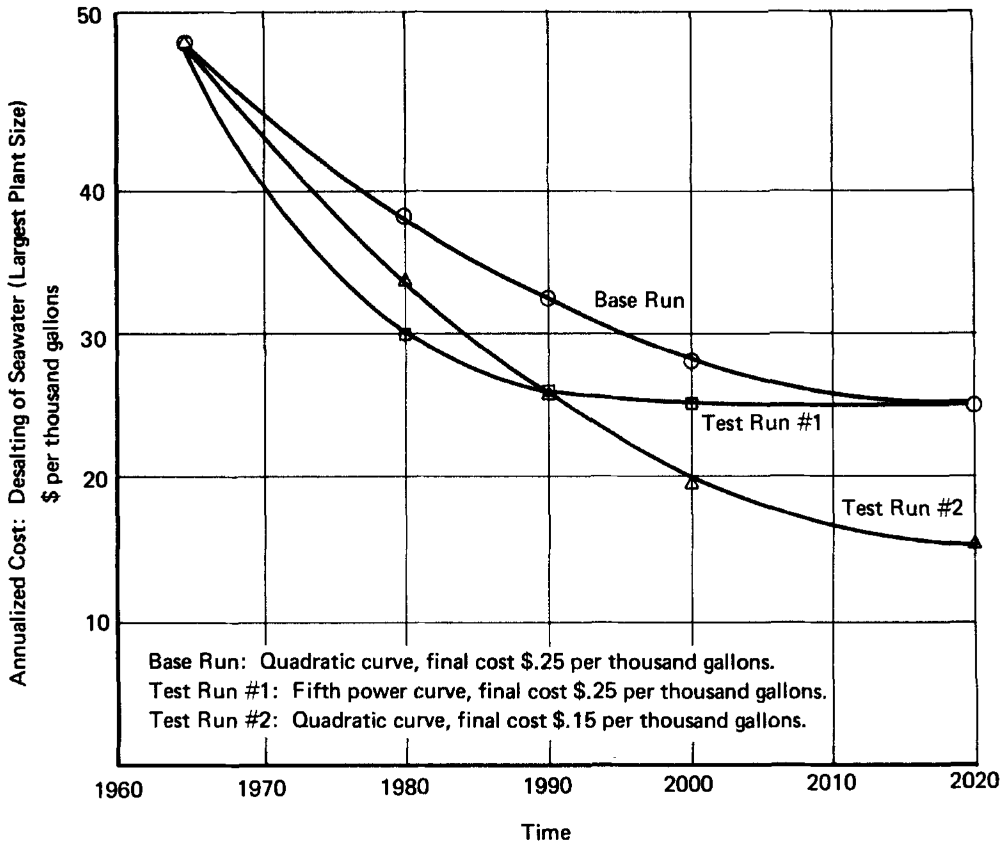

Fig. 4. Different projections of desalting costs used in test runs.

Test Run 2. Lower Eventual Desalting Costs

This run tested the impact of changing from the desalting cost projection in the Base Run (Figure 4) to costs which are substantially lower by 2020 (lower curve in Figure 4). In terms of seawater desalting, this was equivalent to reducing the final desalting cost from 25¢ per 1,000 gallons to 15¢ per 1,000 gallons.

The differences between the results in this test run and the previous test were substantial. The greatest differences in Test Run 2 from the results of the Base Run occurred in the later years of the run. By 1980, this test run projected 25% more desalting capacity. By 2000, the desalting capacity in Test Run 2 was nearly four times that of the Base Run. Similarly, in the 2000-2020 period the total cumulative capacity was more than six times the amount of the Base Run.

REFINEMENT

These forecasts reflect a significant and reasonable role for desalting in satisfying future water needs in this country. Of the total national needs for augmentation capacity between 1965 and 2020, the Base Run estimate of 7 BGD represents about 2% of the total. The effects of improved desalting economics appear to increase desalting's potential by as much as a factor of four or five by the 2000-2020 period. These results have also indicated the ability of the forecasting model to produce interesting insights into the future of desalting.

Much of the preliminary results (particularly the present regional projections) of the model would differ from the intuitive judgment of experienced observers of the desalting scene. The more obvious imperfections are definite reminders that these current results are still preliminary. The objectives of the initial work, however, have been accomplished: (1) to build the model, (2) to demonstrate its capability, and (3) to develop a forecast.

The refinement of the model and the development of an improved forecast is currently underway and will be completed before the end of the year. Improvements in the input data are the most obvious requirements for producing a better view of desalting potential. Information from water resource agencies (i.e., the Bureau of Reclamation, the FWQA, the USGS, and the Corps of Engineers) and the results of other Framework Studies are now being integrated into a model. Further refinements are being implemented in order to provide more reliable forecasts at regional and state levels. More extensive tests of the model are being developed to determine its sensitivity to changes in a wider range of inputs. This sensitivity analysis will indicate the relative importance of each type of input to model results. These tests will thereby guide the selection and development of information which is most relevant to the projection of desalting potential.

This model, by forecasting U.S. desalting potential, will provide OSW with a dynamic tool by which it may guide its program to low-cost water supplies from saline sources. Preliminary results from the model have demonstrated its ability in producing instinctive forecasts as well as in evaluating the role of desalting under a variety of possible future conditions.