THE DESIGN OF WATER SUPPLY SYSTEMS BASED ON DESALINATION

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THE DESIGN OF WATER SUPPLY SYSTEMS BASED ON DESALINATION

Selection of plant sizes and associated storage facilities to meet variations in demand and plant outages

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PREFACE

In the course of the United Nations Interregional Seminar on the Economic Application of Water Desalination, held at Headquarters from 22 September to 2 October 1965, it became apparent that an important topic in the broad field of desalination application requiring further investigation in greater depth was the question of system design of water supply networks based on desalination. Of particular importance in this context was the establishment of criteria for the selection of the number and size of desalination units and for the selection of the amount and type of storage required to provide a system capable of meeting a local pattern of water demand at the least possible cost.

The proposals for such a study contained in the Secretary-General's report on water desalination (E/4142) were approved by the Economic and Social Council in its resolution 1114 (XL) of 7 March 1966. The study was to examine (a) variations in seasonal demand and the extent to which peak demand can be supplied from storage so that investments in peak capacity can be avoided; (b) the capital cost of storage facilities required to enable desalination plants to operate at full capacity and at a high degree of reliability in supply; and (c) the economic and technical considerations involved in the planning of water desalination plants with excess capacity intended to meet projected increases in water demand and to obtain savings through economies of scale.

Accordingly a panel of experts was convened at United Nations Headquarters from 7 to 18 November 1966, composed of the following experts:
Mr. John J.C. Bradbury, General Manager, Bahamas Electricity Corporation, Massau, Bahamas; Mr. Emanuel Lopez, United States Office of Saline Water;
Mr. Patrick A. Mawer, Water Research Association, Medmenham, England;
Mr. Theodore Roefs, California Department of Water Resources, Sacramento, California; Mr. Milton Sachs, United States Office of Saline Water; and
Mr. A. Wiener, Director General, TAHAL Water Planning, Ltd., Israel. Staff members of the Resources and Transport Division of the Department of Economic and Social Affairs also participated in the meeting.

This document contains a summary report of the detailed discussions of the panel meeting as well as additional findings subsequently contributed by the Secretariat.

CONTENTS

ANNEXES

List of Tables

List of Figures

EXPLANATORY NOTES

The following abbreviations have been used throughout the report:

mg	millions of gallons
mgd	millions of gallons daily
gpd	gallons per day

Reference to "gallons" indicates United States gallons, and to "dollars" ($) United States dollars, unless otherwise stated.

INTRODUCTION

During the past decade or so the advances in desalination process technology have been immense. Entirely new processes have emerged and some processes have been dramatically improved in their technical performance and economic viability. The importance of these advances has been reflected in the accumulation of a literature detailing the many researches and improvements in the technologies of the processes. Effort directed at further improvement of desalination process technology continues at an ever-increasing rate, and it is hoped that this will result in continuing reductions in desalination costs, with a parallel expansion of the contribution of desalination to the solution of the problems experienced in many water-short areas of the world.

Recognition of the apparently obvious fact that all efforts in desalination are aimed, ultimately, at the provision of a water supply to some particular demand group exposes the inadequacy of a total concentration on process technology. Of equal importance is the consideration of the system design, where the term "system design" is used to cover all aspects of matching the nature and magnitude of the output from the desalination plant to the nature and magnitude of the demand for water.

Consideration of this aspect of desalination is notably lacking from the literature. For this reason, and in accordance with the policy of advancing the "art of application" of desalination, the Secretary-General convened a meeting of a panel of experts to examine the problem and discuss its many facets.

The nature of the problem

The demand for water in any region or community is, with few exceptions, not of a constant level. In most cases, the demand will have an upward trend of greater or less degree, and superimposed on this long-term change there will be fluctuations in the pattern of demand of an hourly, daily or seasonal nature.

Thus, in planning any water supply facility, recognition must be given to demand fluctuations, and not only to the average demand. Similarly, it is future demands rather than present demands which influence the choice of the water production capacity to be installed. It becomes apparent that a searching analysis of past, present and future patterns of demand is of primary importance in the planning of any water supply system. Given that information can be obtained regarding this demand, it remains to ensure that short-term and seasonal fluctuations in demand can be accommodated within the system.

Fluctuations in demand could, in principle, be accommodated by installing a source with capacity equal to the maximum demand. Clearly, this involves a heavy capital expenditure in the source works, particularly in the case of desalination where unit capital costs of the water production facility are high. An alternative is to build a smaller water production facility, more nearly equal to the average demand, and to invest some of the capital savings in water storage facilities. Peaks in demand can then be met by withdrawals of water from storage, the storage facility being replenished during periods of slack demand.

It is the economic balance between water production capacity and the storage capacity required to accommodate short-term and seasonal fluctuations in demand which forms the first major topic for consideration.

Beyond these short-term and seasonal variations in demand, there remains the long-term trend in demand, or long-term increase in annual demand. Here the choice lies between the frequent building of rather small desalination plants, whose capacity is at all times closely matched to the average demand, and the alternative of the less frequent construction of larger units with the consequent advantage of economies of scale. Against this advantage of economies of scale has to be set the penalty of the correspondingly reduced average load factor resulting from the construction of initially over-sized units. Again an economic optimization is required within this range of alternatives, and the matter is discussed in the report.

The third major aspect requiring consideration in desalination system design is the provision of adequate safeguards on the reliability of the water supply. In general, the maintenance of water supply is of fundamental importance to the economic, social and health standards of a community, and the objective must be to ensure that the reliability of supply is maintained at an appropriately high level. The selection of this appropriate level of reliability, in the statistical sense, is a complex problem in cost-benefit analysis and is not peculiar to the field of desalination. What is peculiar to the field of desalination is the type of failure to which the water production facility may be subject. Unlike a conventional water supply system, a desalination plant is not subject to hydrological deficiencies. It is, however, subject to mechanical failures. These failures may be of an essentially random nature, and in addition the plant must also be taken out of production for some specified period each year for scheduled maintenance. The nature and likely duration of these failures are also discussed in the report.

The impact of these plant failures on the reliability of supply can be reduced by the installation of multiple desalination units, although this carries with it the economic penalty of the higher unit capital costs of smaller units. Again, the alternative exists of installing additional storage capacity to protect the supply against plant failures, and the relative economics of these alternatives are herein investigated.

Method of approach

The panel found that conclusions of a completely generalized nature could not be drawn. The many varied situations of size and pattern of demand, availability of other (albeit in themselves inadequate) supplies of water, and the variability in the cost and feasibility of providing water storage facilities, all result in a need to consider each situation in the light of local conditions. Equally, the rather limited experience so far of the operational reliability of desalination plants, and the way in which this in turn is influenced by local engineering facilities, mitigate against highly specific conclusions of a general applicability.

The approach adopted has been to discuss in some depth the nature of the problem and to highlight the more important factors that must be given detailed consideration. The objective is to provide potential users of desalination with a possible framework of reasoning against which their particular situation may be set.

Further than this, it has been found possible to define with some certainty the appropriate means for accommodating short-term and seasonal variations in demand, and worked examples are included.

In respect of the provisions necessary to ensure reliability of supply against plant failures, rather less specific conclusions must be drawn. As previously stated, a proper analysis of system reliabilities requires a rather complex statistical analysis. [1] It was not the purpose of the panel meeting to conduct such highly specific analyses which, in any case, are made difficult by the extremely limited information available at present on desalination plant failure rates. However, some indications are given of the way in which the installation of twin plants, as opposed to a single unit, may affect the reliability of the over-all system. The cost penalty of using twin plants is evaluated under various conditions and compared with the alternative means of improving the system reliability through the provision of additional storage.

Throughout the report, attention has been confined to the use of multi-stage flash distillation as the source of water. The detailed results must accordingly be interpreted in the light of this qualification. However, the more general discussion is, in the main, applicable to all desalination systems.

1/ For example, see "Relationship between storage capacity and load factor of a desalination plant", by A.R. Golzé, Proceedings of the Interregional Seminar on the Economic Application of Water Desalination (United Nations publication, Sales No.: 66.II.B.30).

SUMMARY OF FINDINGS

The system design of a water supply involving desalination is a complex problem strongly influenced by local conditions. It is therefore recommended that cases be analysed individually, full regard being given to the local pattern of water demand and of the economic and technical environment into which desalination is being introduced.

At a more general level, however, system design can be categorized under the following three major headings:

(a) The provisions necessary to meet short-term and seasonal variations in water demand;

(b) The provisions necessary to ensure continuity of supply during desalination plant outages;

(c) The provisions necessary to meet future long-term increases in demand.

Proper consideration of these three factors forms the basis for determining feasible and economic values for the two major system variables, namely (a) the number of units and the total capacity of desalination to be installed; (b) the amount and type of storage to be installed.

Determination of these variables presupposes knowledge of the following:

(a) Demand characteristics - existing and expected future levels, including details of short-term and seasonal variations;

(b) The types and capacities of storage which can be made available locally, and the costs of these various facilities;

(c) The likelihood and duration of periods of downtime to which any desalination plant configuration may be subject.

The report discusses these three factors, as summarized below, before proceeding to the determination of specific plant/storage configurations.

The interaction of these factors on the determination of optimum plant/storage configurations is overridingly influenced by the existence or otherwise of any other (conventional) sources of water. Accordingly, three distinct types of situation have been considered, as follows: (a) desalination as the sole source of water supply; (b) desalination in conjunction with ground-water supplies; (c) desalination in conjunction with surface-water supplies.

Analysis of current and future water demand

Careful estimation of current and future demand patterns is of special significance in water supply systems involving desalination. An underestimation of demand, leading to the installation of insufficient water production capacity, results in the same problems and penalties as do water shortages in any water supply system. However, the economic penalty of any overestimation in demand can be many times that of a similarly over-sized conventional system due to the very much higher unit capital costs of desalination plant.

Accurate estimation of further demands can never be assured, but is especially subject to error on the introduction of desalination. Where desalination is to become the major source of supply, pronounced changes in the local cost of water can be expected. If these costs are passed on to the consumer, the increase in water prices can be expected to depress per capita consumption. Examples already exist where the replacement of an existing supply by desalination has significantly reduced consumption rates, and even greater price-elasticities 1/ of demand can be expected in some developing countries where the per capita payment ability is particularly low.

The introduction of desalination may also influence demand trends through the resulting change in the quality of water supplied or through a change in the reliability of the supply. The magnitude of these effects is extremely difficult to determine in general and remains difficult even in specific cases.

The foregoing considerations probably invalidate the estimation of future demands by a simple extrapolation of past growth rates in over-all water demand.

The alternative approach is recommended of subdividing demand into its component elements and estimating the growth of these elements individually in the light of conditions relating to these specific demands. By this means, account may be taken of expected population and industrial growth rates, and an improved assessment can be made of the response of various consumer groups to changes in the prices, quality and reliability of water supply.

Where no local experience exists as a basis for estimating price-elasticities of component demands, some guidance may be obtained from analysis of experience in other areas which are closely matched in their economic, social and climatic conditions. Unfortunately, little such experience exists in the developing countries where desalination may have application and where the impact of marked changes in water prices may be most significant.

The most assured method of predetermining price-eleasticities of demand would be to increase local water rates to a level close to those which would otherwise be experienced subsequent to the introduction of desalination. Observation, over one or two years, of the response of demand to new water rates would be invaluable in determining the future need for desalination. While this policy would undoubtedly meet its objective, and in any case might be justified on the more general economic basis of using price as a demand regulator, its adoption is likely to meet with considerable resistance in many areas.

1/ The term "price-elasticity of demand" is used to describe the degree to which demand is influenced by price; a high elasticity implies a strong interaction between demand and price.

Storage facilities

Storage facilities may be classified under the following broad headings: (a) conventional surface storage facilities; (b) underground storage in aquifers or other natural geological formations; (c) non-conventional storage facilities.

Conventional surface storage facilities usually take the form of fabricated steel or concrete tanks in capacities of up to about 20 million gallons, and occasionally extending up to 100 million gallons. Unit capital costs, under typical United States construction conditions, range from about 10 cents/gallon for tanks of 0.2 million gallon capacity down to about 2.5 cents/gallon for tanks of about 20 million gallons (see figure I). Costs in other areas may vary quite considerably from these figures due to local differences in materials and earth-moving costs.

Where storage volumes approaching 100 million gallons or more are required, it is usually found more economic to construct some form of excavated and leveed or dammed reservoir, rather than to employ fabricated tank structures. Costs of these excavated or dammed reservoirs are strongly sensitive to local conditions of topography and surface geology. However, assuming favourable conditions and United States prices, unit capital costs of such reservoirs may drop below 1 cent/gallon (see figure I). Use of these "natural" reservoirs may result in some deterioration in the quality of the stored water.

Underground water storage in natural rock formations or aquifers is being increasingly recognized as a possible alternative to the more conventional surface storage of water. Artificial recharge schemes are currently under development in several parts of the world; most of these schemes are aimed at the seasonal storage of natural water at times of high stream flow for subsequent recovery during periods of low flow. The hydro-geology of natural aquifers varies over such a wide range that generalizations on the feasibility and costs of recharge are impossible. However, under favourable conditions, it seems that the costs of underground storage could be very much lower than those of long-term conventional surface storage. It is therefore recommended that the feasibility and cost of the underground storage of desalinated water be investigated, particularly where a demand of high seasonal variability has to be met from desalination as the sole source of supply.

During the past few years a number of entirely new concepts in water storage have been developed. Of these non-conventional storage facilities the most notable is the "water bladder", a development of the dracone. However, by virtue of its less arduous function, the water bladder may be of considerably lighter construction, with a consequent saving in cost. Preliminary manufacturer's estimates suggest that the storage cost of a bladder could be as low as one fourth of that of conventionally fabricated tank structures at capacities of about 0.25 million gallons.

Whatever form of storage facility is selected, special attention should be given to the rather aggressive nature of distilled water. Product water as normally delivered direct from a distillation plant can be corrosive to both steel and concrete, and special protection may be required for structures employing these materials. Alternatively, some form of chemical pacification must be given to the product water before entry to the storage facility. This type of post-treatment may in any case be required to avoid corrosion of the distribution system or undesirable reaction with any existing deposits in this system.

A further important factor in the selection of the type of storage to be employed is the consideration of water losses either through seepage or evaporation. The unusually high cost of desalinated water makes significant losses unacceptable. Losses are likely to be minimal in enclosed structures such as conventional tanks or a water bladder. In earthen reservoirs seepage losses may be so large as to be prohibitive unless effective linings are installed. Similarly, evaporation losses can be prohibitively high, particularly in desert climates. In respect of underground storage, evaporation losses can be entirely avoided if recharge is through wells rather than by percolation ponds.

Distillation plant availabilities and downtime characteristics

Adequately trained operating personnel are essential to obtaining an acceptable level of distillation plant availability. Given this, an availability of 90 per cent should be achievable in areas where good maintenance facilities exist. In more remote areas, availabilities may easily fall to 85 or even 80 per cent due to the longer periods of time required to obtain or install replacement components following plant failures.

Provision should be made for taking the plant out of operation for a period of scheduled maintenance each year. Typically, this period of scheduled maintenance can last anything up to about three weeks.

Provision should also be made for unforeseen shutdowns of the plant at other times. Most frequently these forced outages will last from a few hours to a few days. It must however be accepted that there can be occasional major component failures which could involve longer periods of downtime ranging up to a few weeks. The maximum duration of such outages is strongly influenced by local conditions, being essentially the time taken to obtain and install a major component replacement, such as a recycle pump.

Major plant failures, such as the destruction of a boiler plant, cannot be provided against by any form of spares-stocking policy or any normal water storage facility. The possibility of such catastrophic plant failures may invalidate the single-unit use of desalination as the sole source of water supply. Where no other water sources exist, it may be necessary to adopt multiple units even though this involves an increased water production cost.

Desalination as the sole source of water supply

Where desalination forms the sole source of water supply the situation calls for the most careful planning of the system design. In particular, it must be ensured that the system is capable of meeting short-term, seasonal and long-term variations in demand at all times, including those times when part or all of the desalination capacity is out of operation undergoing maintenance.

The report shows that under all but rather extreme conditons, short-term variations in demand, lasting anything up to a few days, should be accommodated through the provision of storage rather than through the installation of additional desalination capacity.

Under the wide range of conditions investigated in the report, it has been found that the provision of storage to meet pronounced seasonal variations in demand is uneconomic except where storage is available at very low unit capital costs. Actual break-even storage capital costs vary with particular conditions, but rarely exceed about 2 cents/gallon. Thus, unless storage is available at a very low cost, it is likely that the optimal policy will be to install desalination plant capacity sufficient to meet peak seasonal demands. It is recommended, however, that each case be analysed in the light of its particular conditions.

In respect of the provisions necessary to ensure continuity of supply, no such definite conclusions can be drawn. However, some simplified methods for determining this storage requirement are given in the report together with results for a variety of specific conditions (see table 4 in annex V).

As a means of improving the reliability of the system against plant failures, or as a means of reducing the storage required to ensure a particular level of reliability, the policy may be adopted of installing "half-size" units in place of a single "full-size" unit. To be justified, the benefits of this policy must exceed the water production cost penalty associated with the use of smaller units. These water production cost penalties are readily calculable (see table 5 in annex V), whereas the benefits in terms of improved reliability are not so easily quantified. From the investigation of a number of situations, it seems unlikely that twin units could be justified at demands of much less than 1,000 million gallons per annum on the basis of short-term system reliability. (At lower demands, distillation plant capital costs exhibit such marked economies of scale that the use of half-size units is rarely economic.) However, where protection is required against a catastrophic plant failure, involving months of downtime, there may be no alternative to the installation of multiple units. Similarly, considerations of long-term system design, as discussed later, may lead to the installation of twin units at the initial introduction of desalination as the sole source of water supply.

Desalination in combination with ground-water supplies

Where the introduction of desalination is contemplated in an area at present supplied from ground-water sources, it is recommended that the possibility be investigated first of overdrawing the ground-water field beyond the safe perennial yield to exploit the one-time stock of water in the aquifer. This overdrawing should only be undertaken in areas where a good knowledge of the aquifer hydrology exists; particular caution should be exercised in coastal regions. However, given favourable hydrological conditions, the benefits of temporary overdrawing are:

(a) The postponement of desalination plant construction with consequent conservation of capital and saving in annual operating costs;

(b) The possibility of subsequently obtaining a cheaper and better plant as a result of technological advance.

With the eventual introduction of desalinated water the ground-water withdrawal rate can be reduced to the safe perennial yield, thus freeing a considerable spare withdrawal capacity in ground-water installations, which may then be used for the following purposes:

(a) To make available seasonal peaking capacity which can be drawn on to make up deficiencies between the capacity of the desalination plant and the seasonal demand curve;

(b) To make available stand-by capacity for periods of planned and unplanned outages of the desalination plant;

(c) To make available recharge capacity for storage underground of any surplus water that might be available in the early operational phases of the desalination plant, when demand is below the combined capacity of the desalination plant and the ground-water resources.

Where local ground-water resources are available but are too highly brackish for direct use, considerable savings in over-all water costs can be achieved through the blending of this cheap source of brackish water with the output of the distillation plant.

From the foregoing statements it is clear that considerable scope exists for the improvement of the economics of a desalination system when other sources of supply, such as groundwater exist. However, each situation requires detailed analysis if the full potential of the combined system operation is to be exploited.

Desalination in conjunction with surface-water supplies

The operation of a desalination plant in conjunction with an impounded surface-water resource can show very significant economies over desalination as the sole source of supply.

The need for additional storage, either to meet peak seasonal demand or to sustain the supply during periods of plant outages, is largely avoided by virtue of the existence of the conventional reservoir.

A further considerable advantage can arise from the opportunity to reduce production of water from the desalination plant during periods of high run-off in the conventional catchment. In this way a large part of the operating cost of the desalination plant may be avoided. To exploit this concept successfully in practice requires an "operating rule" to define when the desalination plant may be withdrawn from operation without threat to the reliability of the over-all supply. Methods for establishing such operating rules have recently been developed and shown to be capable of reducing the costs of the incremental supply to as low as 60 per cent of the alternative cost of providing the same incremental supply by desalination alone.

Again it should be emphasized that each case will require individual analysis if the full advantages of multiple-resource development are to be exploited; in particular the potential for the conjunctive use of groundwater with existing surface water should be investigated before conjunctive desalination is considered.

Long-term system design

In order to accommodate future growth in demand, any desalination installation must be sized in excess of current demands. The economies of scale of distillation units encourage a high degree of prebuilding, whereas the economic penalties of low load factor operation encourage a minimal degree of prebuilding. Optimization between these two extremes, through a minimization of long-term costs, is strongly influenced by the prevailing interest rates on capital and by the absolute magnitude of the rate of increase in demand. However, under "typical" conditions, the optimum degree of prebuilding is found to be of the order of eight years; over-all costs are not strongly influenced, however, by a variation of up to about 50 per cent of this period. This relative insensitivity of system costs allows fuller consideration of other factors which may bear on the long-term schedule of plant construction.

A factor encouraging some reduction in the prebuilding period below the "theoretical" optimum suggested above is the prospect of future advances in desalination technology. Clearly, too extended a prebuilding period prejudices the possibility of taking advantage of such developments. For this reason it is recommended that the prebuilding period be reduced, at least to the degree that the relatively insensitive nature of the over-all cost function allows.

If desalination is only required to meet future increases in demand, the policies recommended above of maintaining an essentially constant prebuilding period would, through the course of time, result in the build-up of a number of desalination units each of a comparable capacity. This leads to the development of a system comprised of units which are more or less compatible from the point of view of operation and maintenance. Similarly, the average water cost of the desalination system will exhibit the desirable characteristic of remaining constant or decreasing with time. Inevitably, however, the water cost of the over-all system which includes conventional supplies will probably increase with time as the proportion of desalination in the total system increases.

Where desalination is to meet current demands as well as future increases, the satisfactory development of a desalination system comprised of compatible units is not so readily achieved. If current demands as well as subsequent increases are met by the installation of a single unit, it may be difficult to justify the continued construction of similarly sized units in subsequent years. Clearly, if demand growth rates are slow, subsequent units will necessarily be of far smaller capacity. The report discusses this aspect of system design and shows that it could represent a serious problem unless demand growth rates are of an unusually high order, say 10 per cent per annum or more. At lower, and more common, rates of demand growth, it seems that the first phase of desalination development might best be to install two half-size units to meet current demands and those of the next three to four years. This initial use of twin units, together with a minimal degree of prebuilding at that stage, can reduce the threat of developing a system containing an incompatibly large first unit. Then, under all but near-zero growth conditions, the subsequent installation of units designed to meet the following four to ten years of demand growth results in a system of similarly sized units. The further advantage of installing only a small degree of prebuilt capacity at the first introduction of desalination is that it provides an opportunity to observe the response of demand to any changes in water prices or water quality that arise from the adoption of desalination.

Chapter I

WATER DEMAND

1. Essential to the proper planning of any water supply system, whether it be based on desalination or not, is the careful estimation of present and probable future demands. This assessment of demand is, however, of special importance in the case of desalination. Unfortunately it is also in the case of the introduction of a water supply based on desalination that future demand estimation may be most difficult.

Estimation of future demands

2. As always, an underestimation of demand will lead to water shortages and the accompanying damage to social and economic well-being. However, if excessive measures are taken to avoid these water shortages, the result may be an unnecessarily high investment in desalination plant. Since the unit capital costs of desalination plant are so much higher than those usually associated with conventional water systems, the financial penalties arising from any overestimation of demand will be particularly severe.

3. From this it is clear that the installation of desalination equipment must be preceded by the most careful and detailed forecasts of the future trends in water demand. Unfortunately, in many developing countries where desalination technology has a possible application much of the basic statistical data needed for reliable demand forecasting is not available. The minimum data requirement is a record of the over-all water demand of the preceding several years. Extrapolation of the trend of growth of past demands can then serve as an estimate of future demands. At best, this can only serve as a rough guide to likely future demands, and frequently can give rise to errors which may have a serious effect on the economics of the desalination plant installation, or on the adequacy of the supply.

4. An improvement over this rather coarse estimation of future demands lies in the subdivision of past and projected water demands into separate components corresponding to the various individual water uses within the over-all demands of domestic, commercial and industrial consumers. By the application of detailed information, where available, concerning the possible future behavioural characteristics in each category of water use, and by taking account of the projected growth in population and economic activity, greatly improved estimates may be made of the future trend of each component water use. The amalgamation of these separate trends will then provide an estimate of the future movement in over-all demand. Equally, an identification of the nature of the major components of demand will allow an improved assessment of possible seasonal and daily variations in demand, a knowledge of which is required for the detailed design of the supply system.

Modification of demand trends through the introduction of desalination

5. As discussed above, it is usual to base the estimates of future water demand on an extrapolation of past demands, subdivided into component demands where possible and with due regard being paid to any major changes expected in the growth of population or economic activity. This type of analysis usually proves adequate in the situation where the proposed extension of the water supply system will leave unchanged the nature of the supply and its cost to the consumer. Under these conditions it is reasonable to assume an essentially unchanged response of the economy in relation to water.

6. However, with the introduction of new supplies based on desalination, a completely different situation may prevail. If in the past water was supplied from relatively low-cost natural resources, or conversely was shipped in at exorbitant cost, the introduction of significant quantities of desalinated water can be expected to bring about major changes in the over-all cost of water. Under these circumstances, assuming the changes in water costs to result in similar changes in the price of water charged to the consumer, then it is no longer possible to ignore the price-elasticity of water demand. Significant changes in water prices will not only affect the everyday habits of the domestic water user but will also affect the water-use patterns in commercial, industrial and agricultural applications. Water-saving methods in sewage disposal, such as vacuum conveyance and low-volume flushing, might be adopted, and a pattern of more efficient water re-use in industry is likely to develop under conditions of high water prices. An increase in water prices is likely to have an even greater impact on agricultural users, unless this particular sector of demand is protected through subsidies. 1/

7. As well as producing a significant change in water prices, the introduction of desalination may well produce a marked change in the nature of the supply. Through the partial or total replacement of a brackish-water supply by desalination, the quality of the water will be greatly improved. Similarly, the introduction of desalination into a water-short area can improve the reliability of supply. Both or either of these changes in the water supply could result in marked changes in the demand, although it is difficult to make quantitative estimates of these effects for a general situation.

8. Two particular cases may, however, be quoted where the introduction of desalination was accompanied by a significant change in demand characteristics. In Eilat, Israel, the introduction of increased-cost desalted water into an area previously supplied from highly mineralized groundwater resulted in the adoption of recycling for the evaporative cooler type of air-conditioning together with other measures aimed at water economy. Within one year the total demand for water was reduced by one third. Similarly, with the recent construction of an electrodialysis plant in Buckeye, Arizona, water rates were raised to meet the resulting increase in production costs. This increase in water rates resulted in a sharp fall in water consumption, only partially anticipated, which, by reducing the plant load factor, further increased water costs.

1/ See also "The pricing of water, with special reference to desalination water", by J. Barnea, Proceedings of the Interregional Seminar on the Economic Application of Water Desalination, p. 6.

Estimation of price-elasticity of demand

9. An awareness of the significance of the price-elasticity in the demand for water does little to assist in its quantification. Past experience in this field is extremely limited and is mainly confined to experience in the more highly developed countries. Bearing in mind that elasticities of demand are strongly influenced by the particular water use under consideration, and by the economic and climatic conditions of the demand area, this past experience can have only limited application in the developing countries for which desalination is proposed. However, attempts can be made to divide the demand into its component elements and to estimate the price-elasticity for each component demand from the general consideration of local conditions. This regard for local conditions is of particular significance where the cost of desalinated water to the individual, or to the area economy, would be significant in respect to the income or payment ability. Price-elasticities are likely to be highest under these conditions, and it is also here that a failure properly to estimate price-elasticities will have the most serious economic consequence of over-investment in desalination capacity.

10. A more accurate assessment of the price-elasticity of demand would be obtained by the advanced introduction of higher water rates, close or equal to those which would prevail after the installation of desalination. Observation of the response of demand to such a rate increase, preferably over a period of at very least one year, would be invaluable for the forecasting of future demands. An added benefit might be that the reduction in demand accompanying the increase in water prices might allow the postponement of the high-cost desalination installation.

11. This procedure would undoubtedly provide the most effective means of determining price-elasticities, and in any case might be justified on more general economic grounds as a demand regulator. However, its implementation may be subject to formidable political and social objections in many areas.

12. The foregoing remarks on price-elasticities of demand presuppose that the additional costs of desalination will be transferred to the consumer by direct billings related to the actual consumption of individual consumers. This in turn presupposes the existence of a system of metering. Where metering does not exist, there is a good case for its introduction prior to the installation of desalination because of the reductions in consumption which may thereby be obtained.

13. Where water is distributed from standpipes located in the streets, metering is likely to be impractical as well as unnecessary. The difficulty of carriage from the street to the house will in itself constitute a sufficient curb against waste of water. In some tropical cities where water is supplied free from stand-pipes, _per capita_ consumption is as low as five to ten gallons per day. Under these conditions, water consumption is dependent on the type of plumbing used, the quality of its maintenance and on stand-pipe spacing.

Chapter II

WATER STORAGE FACILITIES

14. Water storage facilities may be broadly categorized as follows: (a) conventional surface storage; (b) underground storage in natural rock formations or aquifers; and (c) non-conventional storage. Conventional surface storage facilities may be further subdivided into fabricated storage tanks and leveed or dammed storage reservoirs. The characteristics and costs of these various types of storage are discussed separately below.

Surface storage facilities - fabricated tanks

15. Although water storage tanks can be found constructed of a variety of materials, most commonly the choice of construction material lies between steel and either reinforced or pre-stressed concrete. The choice will clearly be influenced by the local availability and cost of materials. If United States conditions are taken as representative, it is usually found that, in capacities up to about 1 million gallons, steel tanks have the lower first cost; at larger capacities concrete tanks become a more economic alternative. Typical United States costs for such storage facilities are shown in figure I.

16. In estimating actual costs of storage facilities account must not only be taken of local construction costs but also of the need for protection of the structure against corrosion. In this connexion, it should be noted that distilled water may be highly corrosive to both steel and concrete tanks and special protection must be provided against this corrosion. The cost of protective linings, again under United States conditions, can be as high as $1 a square foot where protection is needed against highly aggressive water. This represents a significant increase in costs over those shown in figure I.

17. Most fabricated water storage facilities, ranging in capacity from a few hundred thousand up to a few million gallons, are used to store treated water for immediate consumption. In these circumstances the storage is usually covered. The use of covered tanks for chlorinated water reduces bacterial infection, airborne contamination and the growth of algae. Evaporation of valuable treated water is also prevented; this is of particular importance where high-cost desalinated water is being stored and where natural evaporation rates are high, such as in arid, desert areas.

18. Most often, storage tanks are roofed in a material similar to that used in the rest of their construction. In these cases excessive roof-spans may be avoided by the adoption of special tank shapes, such as serpentine, anular or other configurations having large volume to roof-span relationships. In many cases tank roofs are designed to make use of light-weight materials such as aluminium or steel sheeting and asphalt-covered plywood. Some experiments are also being undertaken in the use of floating roof covers, thereby completely removing the problems of roof support which, in large structures, may represent a significant cost component.

In a recent example in California, the use of a floating roof on a 110 million gallon storage facility was estimated to reduce the roofing cost to one third of that of a conventionally supported roof structure.

19. In some special cases water storage is provided in the form of elevated tanks. These are more usually constructed of steel and are comparatively expensive both in capital and operating and maintenance costs. They do, however, increase system reliability for fire fighting, maintaining pressure and meeting sudden fluctuations in demand. In view of constructional factors, elevated tanks are usually limited in size to the order of 3 million gallons. With favourable topography, it is sometimes possible to locate surface reservoirs to provide some of the advantages associated with elevated tanks.

Surface storage facilities - leveed and dammed reservoirs

20. For the surface storage of large quantities of water, of the order of 100 million gallons or more, excavated and leveed reservoirs may be used. Alternatively, given a favourable location, a natural depression may be enclosed or dammed.

21. In general, these structures provide means of storing large quantities of water at unit costs very much below those associated with fabricated tanks. Actual costs are strongly influenced by local topography and surface geology and by the availability of earth-moving equipment. Some representative costs, relating to United States conditions, are shown in figure I.

22. Surface reservoirs may be lined or unlined, and the question of whether to line a reservoir will depend on many factors related to the site selected. Among these factors will be water and land values, ultimate cost of lining - including maintenance, turbidity and other water quality requirements, site geological conditions, such as faults and variations in ground-water table, and climatic conditions. Most important is the consideration of water losses from an unlined basin.

23. Hard-surface linings have been constructed of portland and asphaltic cement and mortar, prefabricated asphaltic blocks, brick, stone and soil-cement. These types are generally the most expensive initially, with portland cement concrete lining being the most expensive and with the longest life expectancy when properly constructed. Hard-surface linings are less susceptible to external damage, can be cleaned easily, generally require less maintenance and can frequently be incorporated into the roof supports at the edges of the reservoir. Owing to their inherent rigidity, however, these linings are susceptible to damage by buckling of expansive clays, freezing and thawing, unbalanced hydrostatic back pressures and drying and shrinkage. The aggressiveness of distilled water to concrete is a factor which must also be considered. Soil sterilants are usually used with asphaltic cement linings to prevent damage by reeds and other growths.

24. Asphaltic concrete may be an economical substitute for unreinforced portland cement concrete where the cost of asphalt is sufficiently low to offset a possibly shorter life expectancy and where the aggregate available is suitable for asphaltic concrete but not for portland cement concrete. In mild climates, very good service has been obtained with linings made of a mixture of portland cement and local sandy soil, sometimes at considerable savings as compared with portland

cement concrete. Under more adverse weather conditions, this type of lining has not been entirely satisfactory. The use of pre-cast concrete slabs with proper joint sealers can permit economies of modular construction, reduce the size of equipment needed, permit easier repairs (by replacement) and improve quality control.

25. Membrane linings consist of relatively thin and impervious water barriers, usually covered by a protective layer. Since earth is usually the least costly cover material, it is most frequently used. Buried membranes are almost completely watertight if properly placed and their life expectancy is largely dependent on the adequacy of the cover material used to protect them from weather, erosion and mechanical damages. Depending on the requirements for turbidity and quality control, stored water may require treatment before being used.

26. Membrane linings are highly susceptible to damage by the bleaching action of the water, cleaning operations and puncturing. Rapid fluctuations in the water level will tend to cause the earth cover to slide down the slope. The tendency can be minimized by flattening the side slopes and by selecting free-draining cover materials. Crushed rock or gravel, however, should not be placed directly against the membrane because of the danger of puncture.

27. The various types of membrane linings are hot applied asphalts, prefabricated asphaltic materials, plastics and rubber and layers of expansive clay. They are usually low in original cost, highly impermeable and can be placed in cold or wet weather using simple mobile equipment. Hot applied, catalytic blown asphalt linings have proved to be a low-cost, durable and effective means of seepage control. Because many of the plastic and rubber linings are relatively new, their life expectancy cannot be predicted as readily as those of the hard surface linings.

28. Reports of recently installed buried plastics and rubber film indicate that they are performing very satisfactorily. One advantage of the plastic film is its light weight per unit area, which reduces transportation and handling charges. Exposed plastic linings, however, have generally given poor service due to inferior weathering resistance and high susceptibility.

29. Earth linings consist of compacted earth, loosely placed earth, clay mixtures, and chemically treated soils. When adequate materials are available near the site, earth linings can provide a low-cost, effective seepage barrier. Thick compacted earth linings also can withstand considerable unbalanced hydrostatic pressure, thereby reducing the need for underdrains, and they have low permeability rates. If the job is large enough to warrant the use of heavy earth-moving equipment, relatively low construction costs are possible.

30. Though loosely placed earth is less expensive to place than compacted earth, it is not as impermeable as the latter. Clay mixtures under quality control can form an effective low-cost lining when the proper materials are used.

31. Chemical soil sealants, though still in the experimental stage, have shown encouraging results. Application costs are quite low but since retreatment is usually necessary, the cost of treatment over the years would have to be compared with that of a more permanent lining to determine the relative economy. The effect of distilled water on the permeability rate of the treated soil would also need to be evaluated.

Underground water storage in natural geological formations

32. The water-bearing properties of many natural geological formations have been exploited for many centuries through the construction of ground-water wells. By this means access is obtained to the water accumulated in the formation from natural percolation processes. It is only more recently, during the past few decades, that these natural formations have been purposefully exploited as storage facilities capable of absorbing artificially injected water and subsequently allowing the recovery of this water for use at a later date. Schemes are now under investigation for the seasonal storage of massive quantities of water such as are required for river regulation.

33. In general, the materials underlying the land surface fall into one of the following categories: (a) sandy, relatively permeable formations; (b) permeable cavernous formations; (c) fractured rocks; (d) relatively impermeable shales, clays and similar deposits; (e) deposits of salines such as rock salt and gypsum.

34. The water-bearing properties of these materials can differ radically, the least permeable yielding only a trickle of water to a well whereas the most permeable often produce thousands of gallons per minute to a single well. The withdrawal of water from a well is a process which obeys strict hydraulic laws, and the branch of ground-water science devoted to this process has been developed to a refined level in recent years. Where knowledge is available on the permeability, storage characteristics and aquifer thickness, it is now possible to estimate with some exactitude how a system of wells will function and what changes will occur in the aquifer under various patterns of pumping. By the same means it is also possible to predict what will happen if water is deliberately injected into a well instead of withdrawn from it. When water is pumped into a well in this way it flows through the earth away from the well displacing the original water in the aquifer and pushing it away in all directions. Comparatively little mixing occurs during this process since groundwater is subject to laminar flow and does not undergo turbulence as it moves through the earth materials. If an aquifer is highly permeable and the static ground-water level is at a reasonable depth below the land surface, then water can be stored simply by pouring it into the well and allowing it to enter the aquifer under gravity. If the permeability is low or it is desired to inject at a very high rate, then it may be necessary to force the water into the well under pressure with a pump. In general any given well should accept water at the same rate as it can be pumped although in practice a variety of problems can arise to prevent the attainment of this ideal. The chief difficulty arises from plugging of the well and it is therefore absolutely necessary to eliminate suspended solids in the water to be injected. The presence of air in the form of small bubbles can also cause severe blocking. Unblocking can in many cases be carried out by pumping from the injection well periodically.

35. Further difficulties may arise from the lack of chemical compatibility between the injected water and the substance into which it is injected.

36. An important requirement for injection wells is that the hydraulics of ground-water movement should be understood in as great detail as possible. Groundwater moves through productive aquifers typically at a rate in the order of a fraction of a foot per day. In deep-lying consolidated formations the rate of movement may be no more than a few feet per year. This underground water movement has particular significance to the storage of expensive distilled water since underground drift

which has taken place between injection and pumping may render some of the initial water charge irrecoverable.

37. In formations that are under pressure the injection well will have penetrated one or more confining layers of fine materials often called the "clay cap". If in the vicinity of such a well a structural weakness exists it can give rise to two main problems. First, it may provide a channel for considerable leakage of natural or injected water from the pressure aquifer to overlying materials where it may be of little or no value or where it might cause such problems as high ground water. Secondly, under the high pressures that exist during injection, movement of water through the area of weakness may cause erosion of the fine materials and eventually a structural failure at this point.

38. Because geologic and ground-water conditions differ radically from region to region it is not possible to establish a definite cost for an underground storage system until a particular site is studied in detail. However, many coastal locations appear to be suitable sites for desalination plants and also to present good possibilities for underground storage projects. Since the ocean shores in many parts of the world are underlain by stratified sediment it should be possible to locate one or more permeable formations that could be recharged at relatively low cost. Highly permeable aquifers at very shallow depths offer the least expensive solution for underground storage of demineralized water whereas deep aquifers of low permeability would require a relatively expensive installation.

39. Despite the very great variability between aquifers in practice, for the purposes of illustration, a specimen calculation has been made in annex V for what might be considered a typical recharging facility.

40. On the basis of this specimen calculation, which in particular assumes full recovery of the injected water, it seems likely that the seasonal or long-term storage of water in natural underground formations could show considerable savings over the use of conventional surface storage facilities. It is rather less likely that short-term underground storage could find much application due to the relatively high operating cost associated with frequent transfers of water to and from an aquifer.

41. Finally, it should be stressed that successful operation of a recharge facility cannot be predicted without some form of pilot operation to determine what percentage of stored water may be lost. Such detailed exploratory work is likely to be costly and, unless much of it has already been undertaken in previous searches for naturally occurring groundwater, this investment must be set against the possible savings in the cost of installing conventional surface storage facilities.

Non-conventional storage facilities

42. The type of non-conventional storage facility which perhaps offers considerable promise in developing countries is the "water bladder". These bladders or plastic balloons are a development of the dracone which has been used in a number of parts of the world for the sea transportation of various liquids. However, a considerably lighter standard of construction is adequate where the requirement is only for water storage rather than transport. In the construction of dracones

for the transport of liquids, allowances have to be made for the stresses arising from towing and from the wave action normally to be encountered in open seas. In the case of a water bladder, it is envisaged that the bladder would be tethered immediately off-shore on the sea bed and would not be subject to the same wave action. Alternatively, where local conditions were favourable, the bladder could be accommodated in a relatively cheap surface excavation, the bladder being protected against puncture by the subsoil by effectively floating it in a "pool" of, say, sea water in the excavation.

43. The use of such water bladders is at an early stage of development. However, recent manufacturers' estimates of prices are as low as one fourth of the average cost of steel or concrete tanks at capacities of about 250,000 gallons.

Chapter III

DISTILLATION PLANT AVAILABILITIES AND DOWNTIME CHARACTERISTICS

44. To determine with confidence the measures necessary to ensure the reliability of a water supply based on desalination requires a highly sophisticated level of information on the nature of all failures to which the desalination plant may be subject. Although knowledge of average availabilities may be sufficient to determine a lower level to the capacity of plant needed to meet any demand, far more detailed information on individual plant downtimes is required to assess the day-to-day reliability of the system. In principle, what is required are reliable estimates of the probabilities of any unit being out of service for one hour, one day, one week or any other intermediate or longer period of time. Furthermore, it is necessary to know how these various probabilities are influenced by such factors as the time elapsed since the last major overhaul of the plant.

45. The foregoing outline of plant failure data requirements, formidable though it is, only refers to the case of a single desalination unit. It is felt that the installation of twin half-size units would do something to improve the over-all system reliability. However, in order to quantify this improvement and thereby determine whether the additional cost of twin units is justified, further information is required from that of a single unit. A simple statistical combination of the single-unit failure rates, as well as magnifying any errors in the data relating to individual units, is probably inappropriate due to the interactions between twin units; for example, in the case of the simultaneous failure of both units it is often possible to bring one unit back on to line through the interchangeability of components between the two identical units.

46. In practice the extremely detailed information outlined above cannot be obtained. Multistage flash distillation units have only been in operation since about 1960, and even in the short intervening period such marked changes in plant design and construction have taken place that the older units are no longer represenative of current systems. In addition, plant reliabilities are known to be strongly influenced by local conditions, such as the scaling and other properties of the local sea-water supply, and the degree of operating expertise and level of maintenance facilities available at the particular site. Perhaps most important of all, in the past no effort has been made to collate the experience of plant operation at the various desalination sites, although this omission is now being corrected. 1/

47. As mentioned previously in the report, this apparently intractable position in respect of plant failure data has been partially resolved by recognizing that

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1/ The Resources and Transport Division, Department of Economic and Social Affairs of the United Nations Secretariat, is currently undertaking a world-wide survey of desalination plant operating experience. A report of the first survey, which will be up-dated annually, will be published shortly.

the performance of the system is dominated by two factors. These factors are the average availability of the plant and the duration of the most extended periods of downtime which are likely to be experienced in any plant configuration. To an approximation, design of a system in accordance with these criteria will usually be sufficient to ensure reliability against the other minor failures which may be experienced in practice. Accordingly the over-all availability and the duration of plant failures are now discussed.

Average availabilities of distillation plant

48. Under good conditions, plant availabilities of 90 per cent have been reported as being achievable with a good degree of certainty. Availabilities of this order have been consistently achieved over the past few years in areas such as Kuwait. This, however, corresponds to operation in an area where a high level of plant experience exists and where there are good engineering facilities for maintenance. The use of a 90 per cent availability also assumes that the desalination plant has passed the period of initial "teething troubles" which sometimes follows the installation of a new plant.

49. In areas lacking the advantage of past experience in desalination, and at locations which are remote from adequate maintenance facilities, the achievement of a 90 per cent availability may be difficult. Certainly with inadequate operating know-how the plant availability can drop to an alarmingly low level; it is a prerequisite of successful operation that a sufficient level of operator expertise be established as rapidly as possible. There are, however, only limited measures which can be taken to mitigate the disadvantages of a remote location. Clearly under these circumstances there is an incentive to carry a more extensive stock of spares, although ultimately there must still be items which have to be shipped in on demand with a consequent delay. Probably even more difficult than the supply of engineering spares to a remote location is the supply of skilled personnel to undertake the servicing duty. While it may be possible to train local labour for plant operation, plant maintenance usually demands a higher level of skill which may not be available locally. In any case few desalination installations are sufficiently large to justify the retention on site of all of the servicing skills which may be demanded, and some delay on servicing in remote areas must be accepted.

50. Thus while it is assumed that an adequate level of operator training must be achieved whatever the location of the plant, plant availabilities may still be unavoidably lower than the 90 per cent figure quoted above. In more remote areas, availabilities could easily fall to 85 or 80 per cent.

Distillation plant downtimes

51. Normal operating practice requires that provision be made for an annual period of scheduled maintenance on distillation plant. Sufficient experience exists to indicate that a three-week period should be adequate for this purpose. The annual shutdown allows a thorough inspection of the internal surfaces of flash tanks and water boxes and a restoration of internal protective coatings where necessary. Similarly, condenser bundles can be given proper inspection for tube failures and acid cleaning of any scale deposits. Complete inspection of

ancillary equipment, such as instrumentation, forms the remaining major element of the annual scheduled maintenance.

52. Despite the policy of undertaking annual scheduled maintenance, much of which may be of a preventive nature, a distillation plant will still be subject to enforced shutdowns at times throughout the rest of the year. These enforced shutdowns can be categorized as follows: (a) transient operational failures; (b) replaceable component failures; (c) major breakdowns. In some areas, as well, interruptions of the local power supply may require separate consideration.

53. Transient operational failures arise from essentially trivial faults such as the spurious tripping of safety devices or human error in making an adjustment which may involve the plant shutting down or the production of an unacceptable product quality. Competent plant design would ensure the incorporation of adequate protective devices to ensure that no serious damage to the plant results from this type of mal-operation. Then, under normal conditions, the plant could be restored to operation within a few minutes or at most within an hour or two.

54. Replaceable component failures are likely to occur in a distillation plant in the same manner that they occur in any piece of equipment. Most prone to such failure are components which are subject to high or continually changing mechanical stress. Typically, a bearing or a seal on a pump or an electrical component in some control system may fail. These items are usually inexpensive and can be replaced in a short period of time if available from stock. If the component is not available from local stocks then the period of downtime is a matter of the time taken to locate the required component and transport it to the site. Clearly it is these considerations which will influence the local policy of stocking components. In any case the essential feature of a replaceable component failure is that the total downtime need not exceed some fairly well-defined period. Whether the component be stocked locally or at a distance, if it is obtainable "off the shelf", it can, if necessary, be air-freighted to the site and can be installed within a few days. Thus, the maximum downtime to be allowed for is largely influenced by the local stocking policy and/or the air-freight time between manufacturers' stocks and the desalination installation.

55. A major plant breakdown can, however, be of far more serious consequence. In this category are included major failures which cannot be reasonably provided for, such as the complete destruction of a recycle pump, or serious fire damage to the boiler or distillation plant. It is unlikely that such major replacements could be air-freighted to the site even if they were available for immediate purchase. Where alternative sources of water are available it is conceivable that supply could be sustained, albeit at a reduced level, during the prolonged outage resulting from a major plant failure. Where desalination is the sole source of supply it is difficult to conceive of means of protecting the supply from a single unit against such failures. If such a degree of protection is required it seems inevitable that more than one unit must be installed.

Chapter IV

DESALINATION AS THE SOLE SOURCE OF WATER SUPPLY

56. The situation of desalination being the sole source of water supply calls for the most careful planning of the system design. It is in this situation that no other source of water is available to supplement the output of the desalination plant during periods of peak demand. Equally, no other source of water is available to maintain the supply during periods of scheduled maintenance of the desalination plant or during any other period of downtime on the plant. Thus the full impact of demand fluctuations and plant failures must be absorbed within the desalination system design.

Short-term and seasonal peaks in demand

57. Supply can be sustained under conditions of a variable demand either through the installation of desalination capacity equal to the maximum demand or through the installation of storage facilities, the latter allowing the use of a desalination capacity closer to the average demand. The cost of storage must be weighed against the costs of installing a larger desalination plant, and an economic optimum determined.

58. In the case of short-term demand variations, defined as variations in demand extending over a few hours or a few days, it is almost always more economic to provide storage to meet these fluctuations in demand than to install peak desalination capacity. Computation of the relative costs of the two alternatives will confirm this conclusion under all but the most unusual conditions (see annex II). It is, however, recommended that in all cases the comparison of costs of the two alternatives should be made, using the actual conditions of local demand pattern and local prices of desalination plant capacity and storage facilities.

59. The determination of the optimum means of meeting seasonal variations in demand is not so readily defined. Again it is emphasized that individual cases should be judged in the light of local conditions, a careful comparison being made between the annual charges arising from the alternative investments in storage capacity and additional plant investment.

60. In order to indicate the likely outcome of such a comparison under the various conditions more normally encountered in practice, some generalized calculations are included in annex III. The annex also serves to demonstrate the nature of the cost comparison to be made under any other specific set of conditions.

61. The generalization made in annex III is to assume that seasonal variations in demand may be characterized by a sine wave variation superimposed on a constant demand. Although real demand curves are unlikely to match this sine wave variation with precision, this type of generalized curve is an adequate representation of many of the seasonally varying demands which are met in practice. Examples of the curves are shown in figure II, where it is seen that all situations ranging from essentially uniform to excessively peaky demands have been considered.

62. Figure IV shows the way in which the storage required to meet these peak demands varies with the size of the peak and the plant availability. The costs of these amounts of storage may be calculated by reference to figure I, which shows typical storage capital costs under United States conditions; alternatively, more appropriate local unit costs of storage may be applied.

63. These costs must then be compared with the additional cost associated with the alternative policy of installing peak desalination capacity and no storage. These alternative costs are also calculated in annex III and are shown in table 2 in annex V.

64. Clearly where the costs of peak storage exceed the costs of additional plant capacity the optimum policy is to install peak desalination capacity rather than storage. Results of such a comparison, using various storage costs and the desalination plant costs given in annex I, are set out in table 3 in annex V. The values tabulated are the amounts (cents/1,000 gallons) by which the costs of installing a minimum-size plant together with storage exceed the costs of installing a peak-size plant.

65. It can be seen from table 3 that the optimum policy is usually to install peak desalination capacity where the local costs of storage facilities exceed a value of about 2 cents/gallon, which will usually be the case. Actual break-even storage capital costs are plotted in figure V.

66. It is only when unit costs of storage fall significantly below 2 cents/gallon that the installation of storage to meet seasonal peaks in demand becomes economic. Such low unit costs of storage are usually only associated with large earthen reservoirs. However, the storage of high-value water in this type of reservoir may be precluded by the seepage and evaporation losses often associated with these structures. The remaining possibility of achieving very low storage costs is through the underground storage of water in natural aquifers as discussed in chapter II.

67. It would appear, therefore, that under most conditions where desalination forms the sole source of water supply, the optimum policy is to install desalination capacity equal to the peak demand rather than to meet these peaks in demand from storage.

System design to cover desalination plant outages

68. The protection of any water supply system against failure is both an important and complex problem. The importance of the problem is self-evident, although the determination of the proper level of statistical reliability to be built into any system is a more general question outside of the scope of this report. The complexity of the problem arises from the various ways in which the components of any water supply system may be subject to failure, and from the ways in which combination of these individual failures may occur through the course of time.

69. The nature of the individual failures, or periods of downtime, that may be experienced in desalination plants is discussed in chapter III. In that chapter it is clearly established that provision must be made for a period of scheduled maintenance of the plant each year. It is further established that an allowance of three weeks for scheduled maintenance should be adequate.

70. In respect of unscheduled maintenance, or plant failures, no such definitive statements can be made. It is commonly accepted that over-all plant availability can range between 80 per cent and 90 per cent, depending on the design of the plant, operator skill and the local availability of spares and maintenance facilities. However, the reliability of supply is not so much influenced by the average availability of the plant as by the duration and time of occurrence of any particular failure. Clearly, comparatively frequent failures each of short duration are more easily accommodated than a single failure of extended duration. It is in the estimation of the likelihood of failures involving protracted periods of downtime that reliable information is lacking at present. Further, it is difficult on the basis of present information to make quantitative estimates of how long-term and short-term availabilities are affected by the installation of twin units of "half-capacity" in place of a single "full-capacity" unit.

71. Despite these many deficiencies in the available information attempts have been made to estimate the storage capacities necessary to ensure system reliabilities against scheduled and unscheduled plant downtimes. The economic penalty of installing twin units as opposed to a single larger unit has also been calculated and compared with the saving in cost resulting from the reduced storage requirement associated with twin units.

72. The detailed calculations are shown in annex IV. Here storage requirements have been calculated on the basis of ensuring continuity of supply against a scheduled outage of twenty-one days and a single period of unscheduled outage of either thirty, twenty or ten days. It is assumed that the scheduled maintenance may be undertaken at the most advantageous time of the year, usually during the period of minimum demand. However, it must be expected that the unscheduled outage can occur at any time of the year. Storage requirements necessary to cover both the scheduled downtime and the unscheduled downtime are shown in table 4 in annex V, based on the condition of the unscheduled outage occurring at the most critical time of year.

73. In general it is found that the installation of twin desalination units reduces the need for storage to cover plant outages. Even if it is assumed that the installation of twin units will do nothing to reduce the duration of the maximum likely unscheduled outage, a saving in storage can still be obtained. This saving is of the order of twelve days under conditions of essentially uniform demand, reducing the zero for more peaky demands. If it is assumed that the installation of twin units will be accompanied by a reduction of ten days in the major period of unscheduled downtime, which is probably the maximum reduction which could be expected, then the saving in the total storage requirement is of the order of fourteen to twenty days, depending on the exact nature of the demand pattern.

74. In order to determine whether the installation of twin units is justified, the savings in cost associated with these reduced storage requirements must exceed the increase in water production cost associated with the use of two smaller desalination units. These water production cost penalties have been calculated in annex IV and are shown in table 5 in annex V.

75. Table 5 allows an immediate assessment to be made, for any local unit capital cost of storage, of by how much the storage requirement must be reduced to justify

the installation of twin units. At a unit capital cost of storage of 3 cents/gallon, typical for large concrete storage tanks, the reductions in the days of storage required must exceed values of about twenty-two, fifteen and eleven days, respectively, for the three rates of demand considered, namely 100, 365 and 1,000 mg/annum. Comparing these values with the maximum savings of from fourteen to twenty days storage likely to be achieved in practice, it is seen that the annual demand must be nearing 1,000 mg before the installation of twin units is justified.

76. Although this general conclusion is a useful indication of what might be expected to pertain to the general case, each particular situation should be assessed in the light of local conditions. It is only by this means that the specific advantages and costs of any particular configuration of desalination capacity and storage facilities can be determined. It should also be emphasized that the existence of any conventional supplies of surface or ground water will strongly influence the optimum design of any desalination system as discussed in the following two chapters.

Chapter V

DESALINATION IN COMBINATION WITH GROUND-WATER SUPPLIES

77. In some instances, it may be necessary to install desalination equipment in a water system previously supplied entirely by ground water from wells. The operational pattern of such a combined system will be mainly determined by the differences in costs of these resources. Under present conditions, the operating cost of desalination plant will be of the order of ten times that of a ground-water source; the initial investment in desalting equipment may be twenty to seventy times that of wells having comparable capacity. In these circumstances, considerable attention must be given to the possibility of so managing the ground-water resource as to postpone as long as possible the installation of an expensive desalination scheme. The benefits to be derived from such a postponement are:

(a) The utilization of larger quantities of cheaper ground water;

(b) The postponement of desalination plant construction with consequent conservation of capital and saving in annual operating costs;

(c) The possibility of obtaining a cheaper and better plant when the order is eventually placed, in view of continuing technological progress.

78. It is usual practice in a ground-water scheme to limit withdrawal rates to those corresponding to the safe perennial yields, allowing a margin of safety for dry season conditions. It is possible, however, with favourable geological conditions, to make use of techniques involving over-pumping in order to postpone the need for desalination. This may be illustrated by considering a water demand concentrated close to the sea, to be used later as the source of raw water for a desalination plant. It is also assumed that the location is not part of a small island complex since this would involve special problems.

79. The normal development pattern of ground water should be drawn up in such a way as to make it possible to minimize the losses of water to the sea, and thereby maximize the amount of water available for use. By over-pumping it is possible to exceed the conventional "safe perennial yield" and make use of the one-time stock of water contained between the original levels and those it is planned to reach under ultimate steady-state conditions. This one-time stock of water will consist of the following three main components:

(a) The volume stored between the original ground-water levels and the levels which must be maintained to prevent an excessive inland encroachment of sea water;

(b) The volume stored between the original and the final steady-state position of the interface between salt and fresh water;

(c) The volume which can be temporarily withdrawn from geological storage beyond the levels defined in (a) subject to a replenishment taking place before the salt and fresh-water interface moves too far inland. As an alternative, this method of "negative storage" may be operated indefinitely by the setting up of a continuous "fresh-water barrier" at some distance from the coast.

80. The utilization of these storage volumes must be accompanied by adequate safety margins to allow for estimating errors and extremely dry climatic cycles.

81. With the introduction of desalinated water the ground-water withdrawal rate can be reduced to the "steady-state" rate, thus freeing a considerable spare withdrawal capacity in ground-water installations, which may then be used for the following three purposes:

(a) To make available seasonal peaking capacity which can be drawn on to make up deficiencies between the capacity of the desalination plant and the seasonal demand curve;

(b) To make available stand-by capacity for periods of planned and unplanned outages of the desalination plant;

(c) To make available recharge capacity for storage underground of any surplus water that might become available in seasonal off-peak periods in the early operational phases of the desalting plant, when demand is below the combined production capacity of the desalination plant and ground-water resources.

82. Case (a) implies that ground water, although far cheaper in cost than desalinated water, would be shifted away from base-load operation to a low-load factor peaking duty, and the expensive desalination plant would operate on base load. This might be the right economic solution if the installation of additional desalination capacity could thereby be postponed. Cases (a) and (b) might occur together and the capacity of the ground-water installation developed in the predesalination phase of operation might prove insufficient to cope with the two cases combined. Under such circumstances, the provision of some supplementary capacity would generally still constitute an economical solution. Case (c) assumes the circumstances of negative storage where ground-water stocks have been over-pumped. With the commissioning of a desalination plant, however, it is possible to take advantage of "positive storage" capacity underground. Under this system, the desalination plant capacity would be large enough to allow ground-water withdrawal to be substantially reduced, thus accumulating reserves underground over a period of several years. When demand exceeded the capacity of the desalination plant and ground-water installation, then these reserves could be brought into use. By this means, it would be possible to extend the staging time between successive desalination plants.

83. In view of the cost differences between desalinated water and ground water, it will usually be advantageous:

(a) To delay the introduction of new desalting capacity until the combined capacity of the existing resources (including the creation of temporary capacity by "negative" or "positive storage") is exceeded;

(b) To create all stand-by capacity for outages and peak demand by using existing ground-water installations or creating new ones.

84. The foregoing remarks apply to a particular set of hydrogeological conditions where large-scale underground storage is practicable. However, a wide divergence of natural conditions is met with in practice and it is not possible to lay down a course of action which can be applied in all cases.

85. Some of the water-short areas in developing countries consist of small islands where the geology is not favourable to the large-scale underground storage of water. In many of these cases the only fresh-water supply consists of a relatively thin layer floating on top of sea water, which pervades the whole of the substrata. Under these conditions it is not possible to create "negative storage" by over-pumping without causing salt-water intrusion of the well field. Similarly, there is a limit to the amount of natural storage that can be accumulated without excessive seepage to the sea. The operation of a desalination and ground-water system in these circumstances must be based upon extracting each year the safe perennial yield of cheap ground water and operating the desalinating plant on reduced load factors. Care should, however, be taken to ensure that the ground-water withdrawal rate is such as to provide at all times a sufficient stock to cover plant breakdowns.

Brackish water

86. When a desalination plant is combined with an originally brackish water supply then a straight mixing of the two sources will result in an improved water quality, particularly if the desalinated water is being produced by distillation at high purity. This condition can give rise to the following methods of operation:

(a) If the desalination plant is kept on base load and the peaks are provided for by brackish water, then quality will vary throughout the year, being worst at times of peak demand and best during off-peak periods. Such changes in quality may be unacceptable to some water consumers such as hotels, that may not be prepared to give inferior water to their most important guests during the busy season;

(b) If water quality is maintained at some figure corresponding to peak conditions with full desalination output, then at other times of the year, to maintain consistency, only smaller quantities of distilled water need be produced.

87. An important point with water blending is that when consumers have become used to a better quality they are unwilling to return, in the case of a plant breakdown, to the level with which they were previously satisfied. It may, therefore, be necessary to guard against plant outages by the storage of distilled water. Costs would be reduced in this way and mixing could take place as the desalinated water was drawn off for use.

Chapter VI

DESALINATION IN COMBINATION WITH SURFACE-WATER SUPPLIES

88. In many locations surface water is available in a fully exploited form or in a form capable, in principle, of further development. Even where the economic limit of impoundment has been reached it is unlikely that the surface water will be fully regulated in the hydrological sense. Thus the yield will still be less than the long-term average run-off in the catchment, and at times, following sustained periods of high run-off, the storage may over-spill.

89. When it becomes necessary to seek new supplies to meet future increases in demands, clearly all possible new sources of water must be investigated. One such possible source may be desalination, and its costs must be compared with those of any alternative supplies. To make this comparison on the basis of the costs of desalination operated as a base-load supply can be seriously misleading. This chapter outlines the way in which very much lower costs may be obtained by the proper design and operation of a desalination plant for use in conjunction with a surface-water impoundment. Under some circumstances costs may be reduced to a sufficiently low level that the conjunctive use of desalination becomes more economic than a continued expansion of conventional surface-water resources where the latter would involve abnormally high storage requirements per unit of yield associated with the near-complete regulation of surface waters.

90. The advantages of the conjunctive use of two hydrologically dissimilar water resources apply equally to the conjunctive use of ground water with surface water. It is assumed that the potential for this latter form of conjunctive use would be investigated fully before considering desalination.

The conjunctive use of desalination with surface-water supplies

91. In order to describe the advantages of operating a desalination plant in conjunction with conventional surface-water resources, it is useful to consider first the normal operation of a reservoir alone. Such a reservoir has a maximum sustainable yield, which is the yield that can be sustained at all times other than during a severe drought - when some small deficit in the supply must be accepted. At other times the reservoir may be capable of supplying more than the so-called maximum sustainable yield, as is evidenced by the fact that the reservoir may over-spill during or following periods of particularly high run-off.

92. Thus the prospect exists of increasing the sustainable yield of a reservoir if a means can be found of supplementing the supply of water during periods of "drought". Clearly, a desalination plant, not being subject to drought in the way that a reservoir is, could fulfil such a role. The potential advantage of such a conjunctive system is that the desalination plant need only be operated on relatively rare occasions; the increased total system yield is maintained, none the less, at all times. In this way the high operating cost of the desalination plant can be largely avoided, and the incremental yield is obtained at a cost considerably below the corresponding base-load desalination cost.

93. The concept of only operating the desalination plant during periods of drought is clearly an over-simplification. To delay operation of the desalination plant until the conventional reservoir system were completely depleted would be unsatisfactory; this would imply the need for a desalination installation with capacity sufficient to meet the total system demand. The capital investment in such a plant would be totally uneconomic, although its operating cost in terms of fuel requirements would be minimal. At the other extreme the alternative exists of installing desalination capacity only equal to the incremental yield, that is, the amount by which the total system demand exceeds the maximum sustainable yield of the reservoir alone. Under these conditions operation of the desalination plant would be required at all times except when the reservoir was over-spilling. Thus this second alternative results in a minimum capital expenditure but only a marginal saving is made in the operating cost of the plant compared with a similar unit operated on base load.

94. In general, neither of these extreme alternatives proves to be optimal. Rather, the optimal configuration is found to be the installation of a desalination capacity somewhat in excess of the required incremental yield but considerably less than the total system yield, and the plant is operated at an intermediate load factor. This implies the need for more sophisticated rules to determine when plant operation is required and when it may be avoided without prejudice to the long-term reliability of the system yield. Methods have recently been developed 1/ which allow the calculation of such operating rules applicable to any catchment for which adequate hydrological records exist. Using these methods, it has been shown that, under favourable conditions, the conjunctive use of desalination can provide incremental yields at costs as low as 60 per cent of the alternative base-load desalination cost.

Other operational considerations

95. In general the seriousness of the incidence of plant outages, both planned and enforced, is likely to be greatly reduced in the conjunctive system compared with the case of desalination as the sole supply. Unless the short-term yield of the conventional system is seriously constrained by the capacity of the trunk distribution system, outages of the desalination plant may be covered by temporary "over-drawing" on the conventional resource. Planned maintenance of desalination units can be scheduled to coincide with the period of maximum spill-over probability of the reservoir and in this way might involve no loss to the long-term yield of the reservoir. In a similar manner seasonal peaks in demand can be accommodated by temporarily over-drawing the reservoir.

96. Additional advantages may exist in the conjunctive use of a dual-purpose power/desalination plant in areas where the maximum demands for power and water respectively occur at different times of the year. Systems can be designed where no water production is required from the dual-purpose plant during periods of maximum electrical demand, the full steam flow of the boiler plant, or reactor,

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1/ See Water Research Association, Desalination as a Supplement to Conventional Water Supply - II, Technical Paper 60 (Marlow, England, 1967).

being used to drive cross-compound turbo-alternators exhausting to vacuum. At periods of maximum water demand the low-pressure turbines can be taken out of service, with the low-pressure steam exhausting from the intermediate turbines being fed to the desalination plant.

97. Clearly, any particular situation requires detailed consideration. However, the methodology previously referenced includes provision for the consideration of the local hydrology of the catchment, the local demand pattern, the provisions necessary for plant outages and for any pattern of restricted use of the desalination plant as might be required in a dual-purpose power/water installation.

98. The foregoing discussion of the conjunctive use of desalination is based on the acceptability of a variable-blend ratio between desalinated and natural water. Although this may be of no serious consequence to domestic consumers, the requirements of certain industrial consumers may preclude the supply of variable-quality water. Under these conditions the desalinated and conventional supplies must be regarded as essentially separate sources.

99. A further factor to be considered in the conjunctive use of desalination is the intermittent nature of plant operation implied in such an installation. Long-term load factors may well be of the order of 20 per cent or less, and there is accordingly a special need for the protection of the plant against corrosion during periods of downtime. A number of methods have been suggested to combat this threat of increased corrosion; one such method would be the drying of the plant with warm air followed by nitrogen blanketing, similar to the practice adopted on power-generating turbines. However, little direct experience exists on this type of operation for flash distillation units, and careful consideration of this factor would be necessary on the part of both manufacturers and operators.

System development under increasing demand

100. As the demand for water grows, rendering the surface-water source sufficient to meet only a small fraction of the demand, the advantage of the conjunctive system is reduced. If the storage in the catchment is local to the demand centre, then this can provide the valuable facility of meeting peak demands and sustaining supply during any desalination plant outage. However, under conditions of greatly increased demand it is probable that the total desalination capacity will be made up of a number of units giving enhanced flexibility and reliability, thereby reducing the problems of plant outages.

101. As an alternative to desalination becoming the major source as demand for water increases, it might be economic to develop an alternative conventional surface source which had been uneconomic at the lower capacities appropriate to previous levels of demand. Under these conditions, desalination may prove a valuable interim source, the larger conventional scheme being postponed until it could be commissioned for operation at a consistently high load factor. This postponement of a large capital expenditure may be of particular value in a developing country with a restricted capital availability. In these circumstances an early retirement of the desalination plant installed as an interim measure may be quite acceptable. The plant design and materials would be based on short-term life expectancy.

Chapter VII

LONG-TERM SYSTEM DESIGN

102. The foregoing discussion has been centred on the design of a desalination system to meet seasonal variations in demand and the measures necessary to ensure system reliability against plant outages. These aspects have been discussed in the context of a demand which may vary within any year, but little or no regard has been paid to long-term trends or increases in demand from one year to the next. Even if it is assumed that the system demand for the accommodation of seasonal peaks in demand and plant outages is unchanged by the existence of a long-term demand trend, there remains the question of how the initial desalination capacity should be sized in respect to future demands.

103. The significant economies of scale of distillation plant offer a tempting incentive to install large units capable of satisfying demands well into the future. Against this advantage of obtaining plant at low unit capital costs must be set the penalty of the reduced load factor which is attached to a high level of "pre-building".

104. The primary basis for determining the optimum degree of pre-building is the minimization of over-all costs through an economic balance between the low unit capital costs of larger units and the improved load factors of smaller units. This minimization of long-term costs has been investigated elsewhere 1/ for the slightly artificial conditions of a demand which increases linearly with time. The optimum degree of pre-building is found to depend on the interest rate applicable to the capital investment and on the absolute rate of increase in demand. As might be expected, a higher degree of pre-building is justified at low interest rates, the penalty of pre-investment being least under these conditions. Equally, there is a greater incentive towards pre-building where the absolute level of demand is comparatively low, it being at these lower levels that the economies of scale in unit capital costs are greatest. More specifically, at an interest rate of 6 per cent, for annual rates of increase in demand of 0.1 to 1.0 mgd, the optimum pre-building period is of the order of eight years. This implies the building every eight years of a unit of capacity sufficient to satisfy demands during the following eight years.

105. More important than this specific result is the finding that long-term costs are only marginally affected by significant departures from the theoretically optimum pre-building period. In some cases the pre-building period may be varied by as much as 50 per cent about the optimum before costs are affected by more than 5 per cent. This leads to the conclusion that the other factors which influence the selection of the pre-building period can be given full consideration without markedly prejudicing long-term costs. These other factors are now discussed.

1/ Water Research Association, op. cit., p. 46.

106. As demand grows within a water supply system, it is clearly desirable that the desalination units installed to meet these increases in demand should be of a capacity comparable to, or greater than, previously installed units. To install units of significantly smaller capacity could result in the serious consequence of an increase through time of the average cost of water from the system, due to the higher unit capital costs of these small units.

107. Equally the introduction of rather small desalination units into a system otherwise comprised of rather larger units can lead to engineering difficulties. The prospects of maintaining spares which are common to all units can be adversely affected, as can the transfer of plant operation experience and know-how from one unit to another. These factors suggest the installation of standardized units. However, complete adherence to this policy would undoubtedly be invalidated by the rather rapid changes which take place in plant design with advances in the technology.

108. The avoidance of a decreasing unit size within the system may be difficult in practice unless appropriate measures are adopted during the initial stages of system planning. To illustrate the situation, the table below has been constructed to show how the total demand changes with time under various compound annual rates of increase in demand. An initial demand of unity is assumed.

Growth of demand under various compound rates of growth

Year	Annual rate of increase in demand		
n	5 per cent	7.5 per cent	10 per cent
0	1.00	1.00	1.00
3	1.16	1.24	1.34
6	1.34	1.54	1.77
9	1.55	1.92	2.36
12	1.80	2.38	3.14
15	2.08	2.96	4.18
18	2.41	3.68	5.56
21	2.79	4.57	7.40
24	3.23	5.67	9.85

109. Under the conditions where a conventional source of supply existed to meet the "initial" demand of unity and where this source is retained in production, then little difficulty exists. Desalination is only required to meet future increases in demand, and the installation of a unit, say, every five years would result in the desired pattern of increasing unit size, near optimal long-term costs and adequate ability to take advantage of future improvements in process design and plant construction.

110. Under the alternative conditions of desalination being required to meet the existing demand as well as future increases in this demand, an appropriate choice of plant sizes and the sequencing of their construction are not so readily apparent. This type of situation arises where the existing, or previous, water demand was met from a highly brackish source, or by the barging in of water, and where this source is to be abandoned in favour of desalination. Under these conditions, if an eight-year programme of pre-building is adopted the result will be the initial installation of a comparatively large unit followed by a series of considerably smaller units. It may be many years before the installed unit size returns to the level of the initial unit. The problem is particularly apparent where demand growth is rather slow.

111. It would appear that the only means of avoiding this major disparity of unit sizes is to meet the initial demand, and that for the next three or four years, by the installation of twin half-size desalination units. Following this, the adoption of say a five or six-year pre-building policy results in compatible unit sizes.

112. Where the absolute demand rate is of the order of 3 mgd, the use of twin units may in any case be justified by considerations of system flexibility and reliability (see chapter IV). However, at lower rates of demand, the installation of twin units can involve a cost penalty which must be set against any benefits attached to a system in which unit sizes remain constant or increase.

113. In summary, it seems that a pre-building period of the order of five years is to be recommended under most conditions. This is compatible with (a) a feasible programme of construction, (b) an operationally workable system which does not involve the use of units at very low capacities in the early years of plant life and thereby avoids problems of plant instability, and (c) a minimization of long-term costs, including the consideration of taking advantage of future technological improvements. In addition, where desalination is to form the sole source of water supply, the initial installation should be of twin half-size units. In this way, protection is provided against long-term plant failures, and compatibility can be assured between initial and subsequent plant sizes.

ANNEXES

Annex I

DISTILLATION PLANT CAPITAL AND OPERATING COSTS

Capital costs

From information supplied by manufacturers of multistage flash distillation units, the following expression has been derived for plant capital costs:

$$\text{Capital cost (\$)} = 290{,}000 \left\{ \frac{\text{Plant capacity, gpd}}{100{,}000} \right\}^{0.71}$$

Costs refer to plants of from 0.1 mgd to 10 mgd capacity purchased on a turnkey basis, excluding steam supply and distillate storage. Tube material is assumed 90-10 copper-nickel, and the performance ratio is taken as 10.

The cost equation is well suited to preliminary cost evaluation exercises, but cannot be substituted for the more detailed cost estimation necessary for particular situations where very different performance ratios and unit prices may apply. It is essential that local costs be used in any calculations made for specific locations.

Operating costs

In order to permit illustrative examples of the calculation of water costs to be made, the following arbitrary values have been assumed for operating costs:

Steam cost: 33 cents/1,000 lb

Other operating and maintenance costs:

12 cents/1,000 gallons at an annual output of 100 mg
10 cents/1,000 gallons at an annual output of 365 mg
8 cents/1,000 gallons at an annual output of 1,000 mg

These costs do not include labour charges, which are strongly sensitive to local conditions.

Amortization of plant capital costs: 9.82 per cent per annum

(corresponding to depreciation over twenty-five years at an interest rate of 6 per cent per annum, plus a 2 per cent allowance for taxes and insurance)

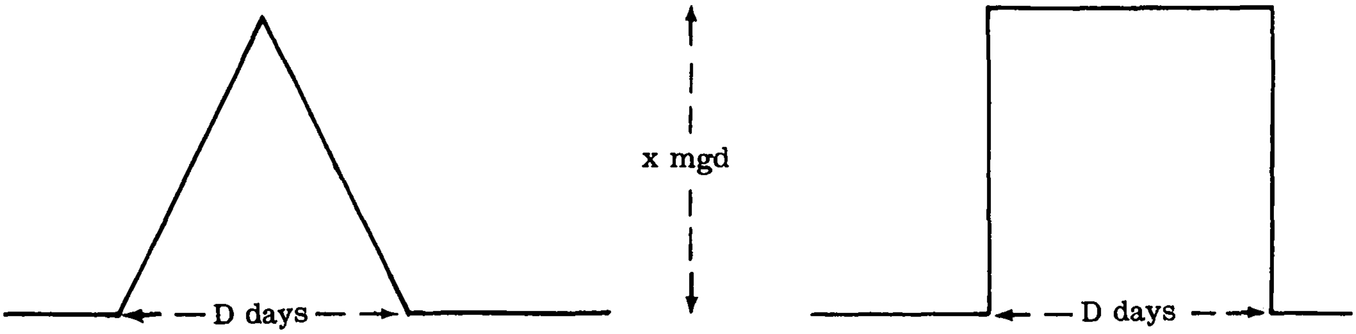
Water costs

Using these bases, water production costs have been calculated for the three annual demand rates of 100, 365, and 1,000 mg. These costs, as shown in table 1 in annex V, contain no allowances for storage, and assume the desalination capacity to be that of a single unit of the minimum feasible size required to meet the average demand. In practice, storage will be required to cover plant outages, and additional desalination capacity must be installed to meet seasonal peaks in demand (see annex III).

Annex II

SYSTEM DESIGN TO MEET SHORT-TERM VARIATIONS IN DEMAND

It is difficult to characterize the nature of short-term demand variations in both a convincingly realistic and a generalized manner. Most simply, the peak in demand can be described as of magnitude x mgd, and duration D days. The actual shape of the peak in demand is likely to be somewhere between the two extremes shown in the figure below



The storage requirement to meet this peak in demand is clearly equal to the area of the peak, that is, it lies somewhere between 0.5 xD and xD mg. The alternative to providing these amounts of storage is to install an additional x mgd of desalination capacity.

A comparison of the annual costs of these alternative investments in storage or plant shows that even if the duration of the "short-term" peak is as much as ten days, the provision of storage is the more economic alternative at costs of storage up to about 20 cents/gallon. On the same basis, if the duration of the peak were reduced to one day, storage would have to cost as much as 200 cents/gallon before the installation of storage capacity became uneconomic.

In practice, storage costs rarely rise above about 10 cents/gallon, and are usually considerably below this value (see figure I). It can therefore be concluded that, under all normal conditions, short-term peaks in demand should be met from storage.

Annex III

SYSTEM DESIGN TO MEET SEASONAL VARIATIONS IN DEMAND

Characterization of demand curve

The term "seasonal variation in demand" is used to relate to the situation where demand is noticeably above average for a significant part of the year.

In order to quantify this type of situation, the demand has been considered as being made up of a constant component, equal to the average demand, on which is superimposed a variable component. The assumption is made that the variable component has the form of a sine wave. Although actual demand situations will depart from this in practice, the choice of a sine wave variation is a reasonable approximation to many real situations and has the further advantage of computational simplicity.

The resulting demand curves are illustrated in figure II in annex V. All situations ranging from a completely uniform demand to a demand of abnormally high variability are shown in the figure, and are analysed in the subsequent computation. The various demand situations are covered by describing the demand by the expression

$$\text{Daily demand} = D\ (1 + k \sin x)$$

where D is the average daily demand throughout the year, and k is a variable which, in principle, can take any value between 0 and 1.

In normal situations the ratio of the peak demand (equal to $D\ (1 + k)$) to the minimum demand (equal to $D\ (1 - k)$) is unlikely to be much in excess of 3. This ratio of peak-to-minimum demand corresponds to the case of $k = 0.5$. Higher values of k, corresponding to a more pronounced seasonal peak in demand, may, however, be encountered in areas where there is a large seasonal influx of tourists. A further factor often resulting in exceptionally high peaks in demand is the presence of irrigation or lawn watering; such water uses are unlikely in the case of high-cost desalinated water.

Comparison of costs using peak desalination capacity and minimum desalination capacity

The difference in water production cost of using peak rather than minimum desalination capacity [a] arises wholly from the additional capital expenditure involved in installing the large capacity, it being assumed that the operating costs are the same in the two cases. This difference in water production cost

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[a] Minimum desalination capacity is equal to D/A, where D is the average demand and A is the plant availability, assumed less than unity.

is calculated here to illustrate the magnitudes of the cost differences involved and for subsequent comparison with the costs of storage implied by the use of a plant capacity below the peak demand.

The amount by which the water production cost (cents/1,000 gallons) from a peak-size plant exceeds that of a minimum-size plant is given by

$$\left(\begin{array}{l} \text{Capital cost (\$) of plant} \\ \text{capacity equal to D (1 + k)} \end{array} - \begin{array}{l} \text{Capital cost (\$) of plant} \\ \text{capacity equal to D/A} \end{array} \right) \frac{\sigma . 10^{5}}{365\ D}$$

where D is the average daily demand in gallons, and σ is the annual fixed charges rate applicable to desalination plant (taken here as equal to 0.0982), and A is the plant availability - assumed less than unity.

Annex I shows that desalination plant capital costs can be taken, assuming a performance ratio of 10, as

$$\text{Capital cost (\$)} = 290,000 \left\{ \frac{D}{100,000} \right\}^{0.71}$$

Thus the difference in water production cost of the peak and minimum-size plants is given by

$$\frac{290,000\ \sigma_1\ 10^{1.45}}{365\ D^{0.29}} \left\{ (1 + k)^{0.71} - \left(\frac{1}{A}\right)^{0.71} \right\}$$

This assumes that, in either situation, the desalination capacity consists of a single unit. If the alternative of using two half-size units is considered, the cost differences would be increased by a factor of $2^{0.29}$.

Using these expressions, the additional costs associated with using peak-size installations are given in table 2 in annex V for a variety of conditions. The significance of these cost differences can be judged by comparing them with the absolute water production costs associated with the use of minimum desalination capacities shown in table 1.

Calculation of storage requirement to meet peak demand (using minimum-size plant)

If peak demands are to be met from storage, rather than through the installation of peak desalination plant capacity, it is clear that an amount of storage equal to the area A in figure III must be provided. The maximum peak storage requirement corresponds to the installation of the minimum feasible sized plant. As shown in figure III the minimum feasible plant capacity is equal to D/A, where D is the average demand and A is the plant availability. Typical desalination plant availabilities are 0.8, 0.85 and 0.9, and the storage requirements corresponding to these availabilities have been calculated.

Referring to figure III, the storage requirement (equal to area A) is given by

$$\text{Area A} = 2\int_{a}^{\pi/2} D\,(1 + k \sin x)\,dx \;-\; 2\left(\frac{\pi}{2} - a\right)\frac{D}{A}$$

$$= 2D\left\{\left(\frac{\pi}{2} - a\right)\left(1 - \frac{1}{A}\right) + k \cos a\right\}$$

Values of "a" are given by the solution to

$$D\,(1 + k \sin a) = \frac{D}{A}$$

That is

$$a = \sin^{-1}\left\{\frac{1}{k}\left(\frac{1}{A} - 1\right)\right\}$$

Results are shown in figure IV, where the peak storage requirement is plotted for all values of k and for the three plant availabilities of 0.8, 0.85 and 0.9. The peak storage requirement is shown in "days of average demand", and hence the figure may be used for any absolute size of demand. For example, where the average demand is 2 mgd a peak storage requirement of, say, 15 days corresponds to the installation of 30 mg of storage.

At low values of k, corresponding to near uniform demands, the peak storage requirement is seen to drop to zero. This corresponds to the situation where even the peak demand is less than the capacity of the minimum feasible plant size, the latter necessarily being greater than the average demand due to a less than 100 per cent plant availability.

Costs of peak storage

The cost of providing peak storage, expressed as the cost in cents/1,000 gallons of total water production, is given by

$$\text{Storage cost (cents/1,000 gallons)} = \frac{X D\, c\, \sigma_2\, 1{,}000}{365\, D}$$

where X is the amount of storage in days of average demand; D is the average daily demand in gallons; σ_2 is the annual fixed charges rate applicable to storage installations, and c is the capital cost of storage facilities in cents/gallon.

Using a value of 0.0834 for σ_2 (equivalent to 6 per cent interest over 50 years + 2 per cent taxes and insurance) gives

$$\text{Storage cost} = 0.2283\ X\ c.$$

Typical capital costs for storage, under United States conditions, are shown in figure I. Local values may be used to calculate the costs of the peak storage requirements in figure IV.

Comparative costs of peak capacity versus storage to meet seasonal peaks

Using the peak storage requirements shown in figure IV and the additional water production costs of using peak desalination capacity shown in table 2, table 3 has been constructed to show the difference in the over-all water cost of the two alternatives. The values shown in the table are:

> The total water cost of installing a minimum-size plant together with peak storage

less

> the water cost of installing a peak-size plant, no peak storage being necessary.

Thus, a positive entry in the table indicates that the use of a peak-capacity plant would be preferable, and negative entries correspond to conditions where the provision of storage would provide a cheaper alternative.

As would be expected, the use of storage becomes economic only when the capital cost of constructing storage facilities is sufficiently low. Figure V shows just how low storage capital costs have to be for the use of peak storage to be economic.

The break-even storage costs are seen to be of the order of 2 cents/gallon or less. It seems unlikely that enclosed storage structures, such as concrete tanks, can be constructed at costs as low as this (see figure I). On this basis the general conclusion can be drawn that seasonal variations in demand, of the type considered here, should be accommodated by the installation of peak desalination capacity rather than through the installation of storage.

A possible exception to this is where storage is available at very low capital cost, say, less than 1 cent/gallon. Such low costs as this are normally associated only with large earthen reservoirs. The use of such structures for the seasonal storage of high-value desalinated water may, however, be invalidated by the losses due to seepage and evaporation frequently associated with these structures.

The further possibility of providing low-cost storage lies in the underground storage of water in water-bearing or dry aquifers. This possibility is discussed in chapter II.

Finally, it should be emphasized that the general policy of installing peak desalination capacity only applies with reasonable generality to the situation of desalination being the sole source of supply.

Annex IV

SYSTEM DESIGN TO COVER DESALINATION PLANT DOWNTIME

The questions analysed in this annex are:

(a) How much storage must be provided to ensure continuity of supply during periods of desalination plant downtime, that is, during periods of scheduled and unscheduled maintenance?

(b) By how much, if at all, can this storage requirement be reduced by the installation of twin half-size desalination units as opposed to a single full-size desalination unit?

(c) Is this saving in storage sufficient to offset the increased cost of installing twin units compared with the cost of a single unit?

As indicated in chapter IV, the determination of storage requirements and system reliabilities is an extremely complex problem requiring for its solution detailed knowledge of the likely incidence of failures of components within the system. Of particular significance is the duration of the most extended period of downtime which is likely to occur coupled with the possibility of other significant outages occurring in close proximity to this major outage. If a system can be designed to withstand this major outage, or succession of major outages, then, to an approximation, it can be expected that any further minor outages which may occur from time to time will be of no serious consequence.

It is this type of approximate analysis which has been adopted in this report. In addition, the following specific assumptions have been made concerning the nature of plant outages against which the system should be designed:

(a) Each desalination unit is subject to a single continuous period of downtime of twenty-one days/year for scheduled maintenance. The time of year at which this scheduled maintenance should be undertaken is at the choice of the operator. Supply must be fully sustained during this downtime;

(b) A further major period of continuous downtime must be expected. This period of unscheduled maintenance may occur at any time throughout the year. Its duration in the case of a single unit, may be ten, twenty, or thirty days (or some intermediate value), depending on local circumstances. Supply must be fully sustained throughout this period of unscheduled maintenance, even when this unscheduled maintenance occurs at a time, with respect to the scheduled maintenance, which represents the most critical condition;

(c) When twin units are installed, the scheduled maintenance of the two units may be undertaken at different times if desired. It must be expected, however, that there will be occasions when both units are out of service simultaneously for unscheduled maintenance. The duration of this major period of unscheduled maintenance on both units simultaneously can be expected to be less than in the case of a single-plant installation;

(d) Other shorter periods of unscheduled maintenance may be required. It is assumed that the storage provided to cover the major period of unscheduled maintenance and the scheduled maintenance is sufficient to cover these other minor periods of downtime;

(e) The total plant downtime, made up of major and minor outages, is such as to result in an average plant availability of 80 per cent, 85 per cent or 90 per cent, depending on local circumstances;

(f) Demand patterns are assumed to be of the same general character as described in annex III, namely, of the form D (1 + k sin x). As established in annex III, the installed desalination capacity is assumed equal to the peak demand.

Storage requirements to cover scheduled maintenance

In the case of a single-plant installation it is clearly most advantageous to arrange for the scheduled maintenance of the plant to be undertaken during the period of minimum demand. Then the storage requirement is equal to the area A shown in figure VI. To a good approximation, this is equal to twenty-one (1 - k) days of average demand.

When the desalination capacity is made up of two half-size units, the best arrangement of scheduled maintenance and the resulting storage requirement are not so immediately apparent. If the minimum demand drops to, or below, half of the peak demand, then again the scheduled maintenance is best undertaken at the period of minimum demand. If the two units are taken out of service in close succession, rather than simultaneously, the supply can be sustained at all times and no storage is required. Thus, under the conditions of a sufficiently variable demand and twin desalination units, the storage requirement for scheduled maintenance is zero.

Where the demand is of a more uniform nature, the storage requirement can be minimized by scheduling the maintenance of the two units as illustrated in figure VII. The maintenance periods of the two units are disposed about the actual minimum in demand in such a way that the areas A, B and C are equal (figure VII). Then, the storage requirement is equal to area A, which to a good approximation is

$$21 \left\{ 1 - k - \left(\frac{1 + k}{2} \right) \right\} = 10.5\,(1 - 3k).$$

This separation of the maintenance periods of the two units has the effect of nearly halving the storage requirement compared with that which would be necessary if the two units were taken out of service in immediate succession or together.

The storage requirements to cover scheduled maintenance can thus be summarized as follows:

Storage requirements (Days of average demand (D)[a])
to cover 21 days of scheduled maintenance

k	Twin units	Single unit	Saving in storage of twin-unit system over single-unit system
0 - 1/3	$10.5\ (1 - 3k)$	$21\ (1 - k)$	$10.5\ (1 + k)$
1/3 - 1	0		$21\ (1 - k)$

[a] Demand pattern throughout year is $D\ (1 + k \sin x)$ (see figure II).

Storage requirements to cover a major period of unscheduled maintenance in addition to scheduled maintenance

Three possible values for the duration of the major period of unscheduled maintenance, namely, ten, twenty and thirty days, have been considered. The choice of the particular value to be used in practice will depend on local circumstances.

The total storage required to cover this unscheduled maintenance as well as the period of scheduled maintenance will depend on when the unscheduled downtime occurs. Where the demand pattern is rather flat, the most critical condition will arise when the unscheduled outage immediately follows the period of scheduled maintenance. Where the demand has a pronounced seasonal peak, the most critical condition will be when the unscheduled outage occurs during the period of peak demand.

These two extremes are illustrated in figure VIII. The area A represents the demand for water that must be met from storage during the scheduled maintenance, as detailed in the immediately previous section. The areas B and C, respectively, represent the demand during the period of unscheduled downtime immediately following the scheduled maintenance or at the time of peak demand.

The total storage requirement to meet both scheduled and unscheduled downtime is therefore given by

Area A + Area B

or

Area C

whichever is the greater (figure VIII).

Area A has already been determined above. To reasonable approximations, areas B and C are given by

$$B = Q\ (1 - k) \text{ and } C = Q\ (1 + k)$$

where $\underline{Q}$ is the duration of the unscheduled outage.

Investigation under the various conditions of demand to determine which of the two conditions of occurrence of the unscheduled downtime is more critical leads to values for the total storage requirement to cover both scheduled and unscheduled maintenance. These values are set out in table 4 in annex V.

Additional water production costs associated with the use of twin desalination units

Although the use of twin half-size desalination units usually results in a reduction in the storage requirement to cover plant outages, especially if the reduced likelihood of a prolonged unscheduled outage of both units is considered, there exists the accompanying penalty of the higher water production costs associated with the use of smaller units.

The cost penalty, expressed as a cost per 1,000 gallons of average demand, is given by:

$$\begin{array}{l}\text{Cost penalty}\\ \quad\text{(cents/1,000 gallons)}\end{array} = \left\{ \begin{array}{l}\text{Capital cost of two units}\\ \text{each of capacity 1/2 D}\\ (1 + k)\end{array} - \begin{array}{l}\text{Capital cost of}\\ \text{one unit of}\\ \text{capacity D}\\ (1 + k)\end{array} \right\} \frac{\sigma . 10^5}{365\ D}$$

where $\underline{\sigma}$ is the annual fixed charges rate associated with desalination plant and $\underline{D}$ is the average demand in gallons per day.

Annex I gives an expression for plant capital cost as

$$\text{Plant capital cost (\$)} = 290{,}000 \left(\frac{D}{10^5} \right)^{0.71}$$

Thus

$$\text{Cost penalty (cents/1,000 gallons)} = \frac{290{,}000\ (1 + k)^{0.71}\ \sigma_1\ 10^{1.35}(2^{0.29} - 1)}{365\ D^{0.29}}$$

Values of this cost penalty are shown in table 5 for various sizes and patterns of demand. Also shown in the table are corresponding values of Xc, where $\underline{c}$ is the unit capital cost of storage (cents/gallon) and $\underline{X}$ is the number of days of storage which must be saved through the installation of twin units for the associated water production cost penalty to be justified. Thus, for example, if storage is available at a capital cost of 3 cents/gallon, where Xc is shown equal to 61.0, the saving in storage must be at least 20.33 days for the installation of twin units to be justified.

Annex V

SPECIMEN CALCULATION OF UNDERGROUND WATER STORAGE COSTS

As stated in chapter II, the character of naturally occurring previous geological formations can differ by several orders of magnitude. As a consequence, the feasibility and cost of using such formations as water storage facilities can vary widely. However, if favourable conditions are assumed, such as those normally associated with a high-yield aquifer located fairly close to surface levels, the following characteristics can be assumed for the purpose of illustrative calculation:

Depth of wells	200 ft
Maximum recharge (or recovery) rate per well	0.5 mgd
Capital cost per well	8,000 dollars
Cost of pumps and controls	3,000 "
Power cost	2 cents kWh
Total pumping head for recharge and recovery	100 ft
Annual fixed charges rate . . . . (assumes 6 per cent interest, and depreciation of well cost over twenty years and of pumps and controls cost over ten years)	10 per cent

Before proceeding to particular cost calculations, the way in which the over-all cost structures of underground and conventional surface storage facilities are fundamentally different should be recognized. In the case of conventional water storage in tanks or surface reservoirs, the cost of storage is essentially a capital cost. This capital cost is entirely influenced by the capacity or volume of the storage structure. The operating cost of the input of water to storage, or its subsequent recovery, can be neglected. Similarly, costs are uninfluenced by the instantaneous rate of transfer of water to or from storage. In the case of underground storage of water in natural formations, the situation is markedly different. Here, both capital and operating costs are encountered. The capital cost is largely a function of the maximum rate of transfer of water required to or from storage, and is uninfluenced by the total volume of water that has to be stored. The operating cost is determined by the volume of water to be stored and the frequency with which this volume of water is put into and recovered from storage.

The particular cost values assumed above imply a capital investment of $22,000 per mgd of recharge facility and an operating cost of about $9 for each million gallons of water recharged and recovered from storage.

In order to determine the annual costs attributable to storage in any system, the patterns of water production and consumption must first be defined. In this way the required maximum rate of recharge, or withdrawal, may be determined together with the amount and frequency of transfer of water to or from storage. Results for one particular example are listed in table 6. The example chosen is of a seasonally variable demand being met from an essentially constant output desalination plant of capacity close to the long-term average demand. Table 6 also lists the equivalent unit capital costs of conventional surface storage facilities which would result in the same annual costs as those of the underground storage, assuming no losses. It is found that, for the particular example chosen, the underground storage system is equivalent to an extremely low-cost conventional system. This suggests that the underground storage of water may well be worth further investigation, at least in areas where the behaviour of local aquifers is fully understood and predictable.

It must be emphasized that the results quoted here apply to a very specific situation for which a number of arbitrary assumptions have been made. In particular, 100 per cent recovery of the injected water has been assumed; any significant losses in practice could rapidly remove any advantages of underground storage.

It should also be emphasized that the apparent cost advantages of underground storage may only apply to the seasonal or long-term storage of water; for short-term storage applications, the relatively high operating cost of such a system can make uneconomic the frequent transfer of water into, and out of, the aquifer.

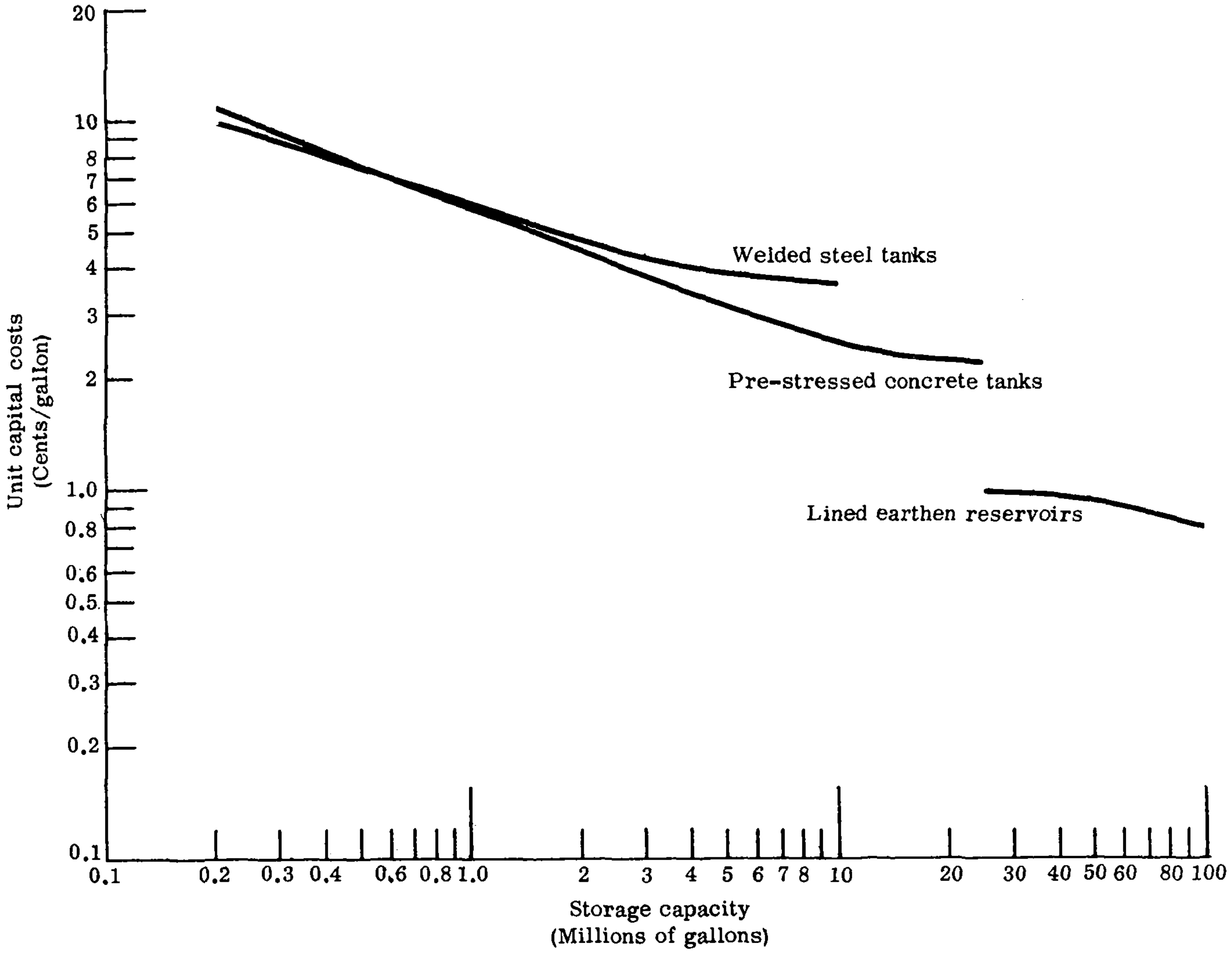

Figure I. Unit capital costs of storage facilities

Note: Values are erected costs in the United States of America

Table 1. Desalination plant costs and water production costs

Annual demand (mg)	Plant availability	Plant capacity (mgd)	Capital cost ($$10^6$)	Capital charges (cents/1,000 gallons)	Total water production cost (cents/1,000 gallons)
	0.80	0.343	0.698	68.5	113.5
100	0.85	0.322	0.665	65.3	110.3
	0.90	0.304	0.639	62.7	107.7
	0.80	1.25	1.77	47.6	90.6
365	0.85	1.18	1.68	45.2	88.2
	0.90	1.11	1.60	43.1	86.1
	0.80	3.43	3.57	35.0	76.0
1,000	0.85	3.22	3.41	33.5	74.5
	0.90	3.04	3.27	32.1	73.1

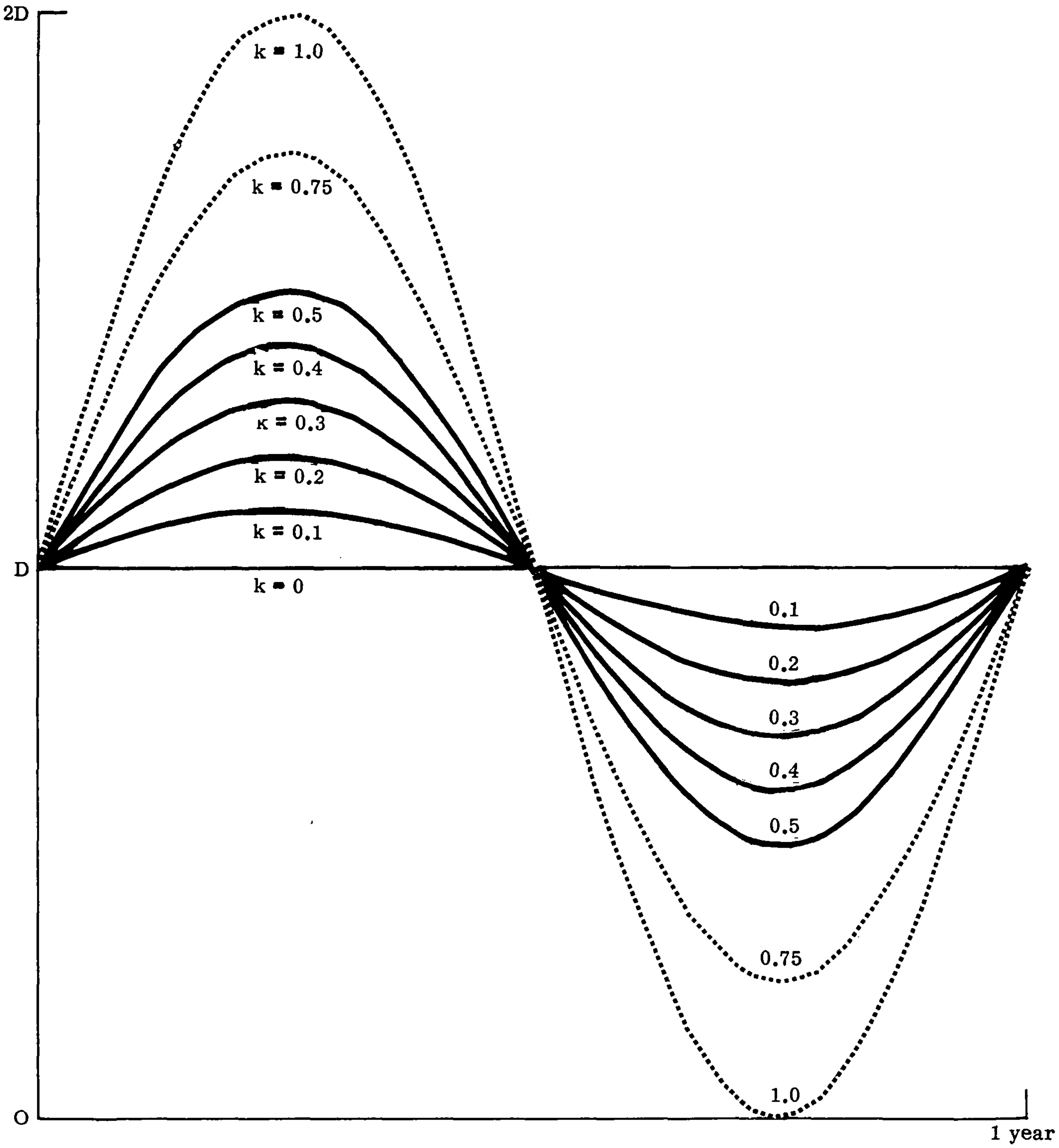

Figure II. Seasonal demand curves - D (1 + k sin x)

Average demand = D

Peak demand = D (1 + k)

Minimum demand = D (1 - k)

Ratio of peak/minimum = (1 + k)/(1 - k)

Table 2. Additional water production cost of using a peak-capacity installation as against a minimum-capacity installation

(Cents/1,000 gallons)

Availability (percentage)	Annual demand (mg)	k[a] = 0.2	k[a] = 0.4	k[a] = 0.6	k[a] = 0.8	k[a] = 1.0
Single-unit installation						
90	100	3.64	11.4	18.8	25.9	32.8
	365	2.56	7.8	12.9	17.8	22.6
	1,000	1.87	5.8	9.64	13.3	16.8
85	100	1.06	8.75	16.2	23.4	30.3
	365	0.73	6.01	11.1	16.1	20.8
	1,000	0.54	4.48	8.3	12.0	15.5
80	100	-	5.75	13.2	20.3	27.3
	365	-	3.95	9.1	14.0	18.8
	1,000	-	2.95	6.8	10.4	14.0
Twin- (half-size) unit installation						
90	100	4.50	14.1	23.2	32.0	40.5
	365	3.16	9.6	15.9	22.0	27.9
	1,000	2.31	7.16	11.9	16.4	20.7
85	100	1.31	10.8	20.0	28.9	37.4
	365	0.90	7.43	13.7	19.9	25.6
	1,000	0.67	5.53	10.2	14.8	19.1
80	100	-	7.10	16.3	25.0	33.7
	365	-	4.87	11.2	17.3	23.2
	1,000	-	3.64	8.4	12.8	17.3

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[a] For significance of variable *k*, see figure II.

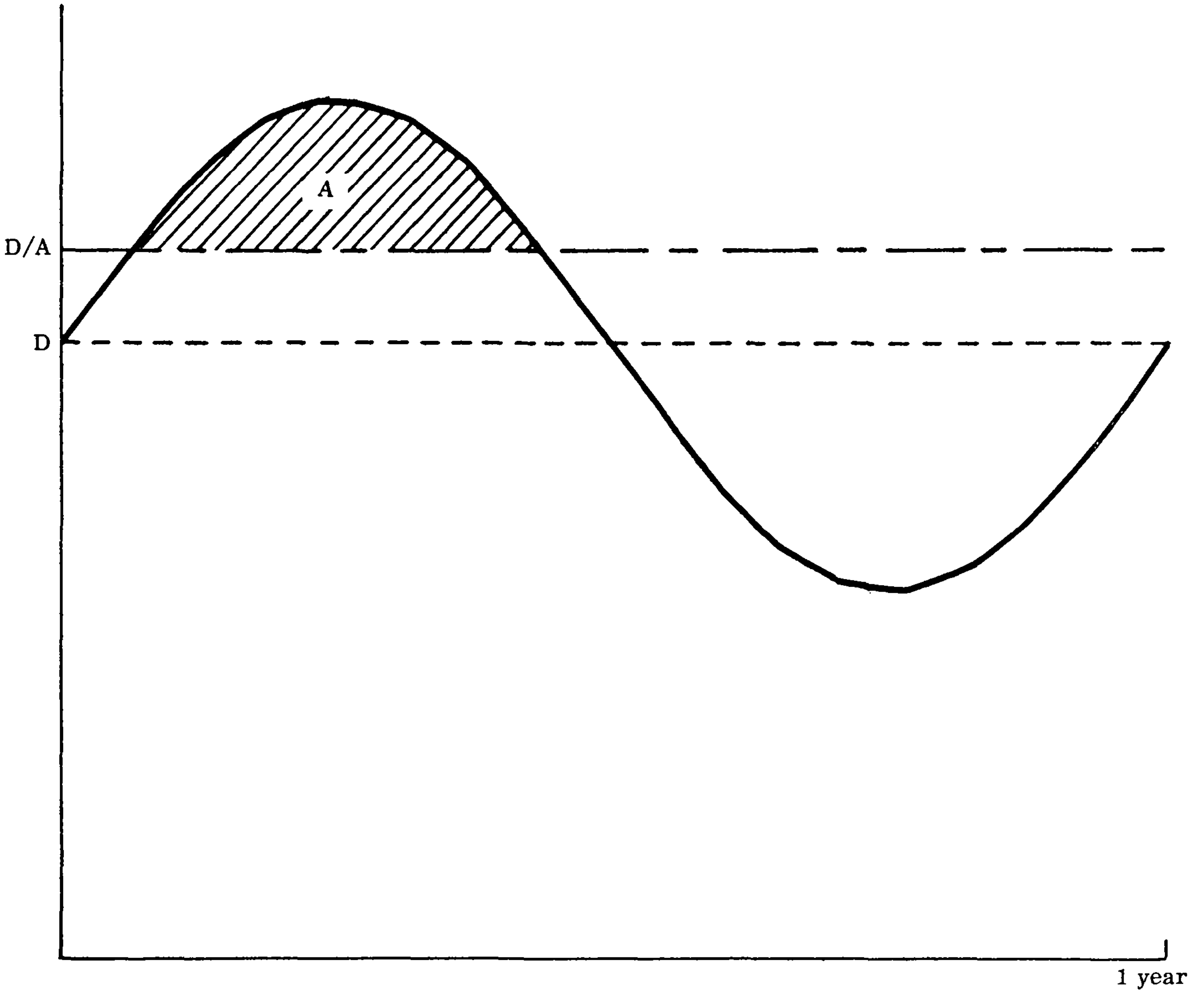

Figure III. Peak storage requirement (area A)

Demand varies throughout the year as D (1 + k sin x), where D is the average daily demand.

Plant capacity is D/A, where A is the plant availability.

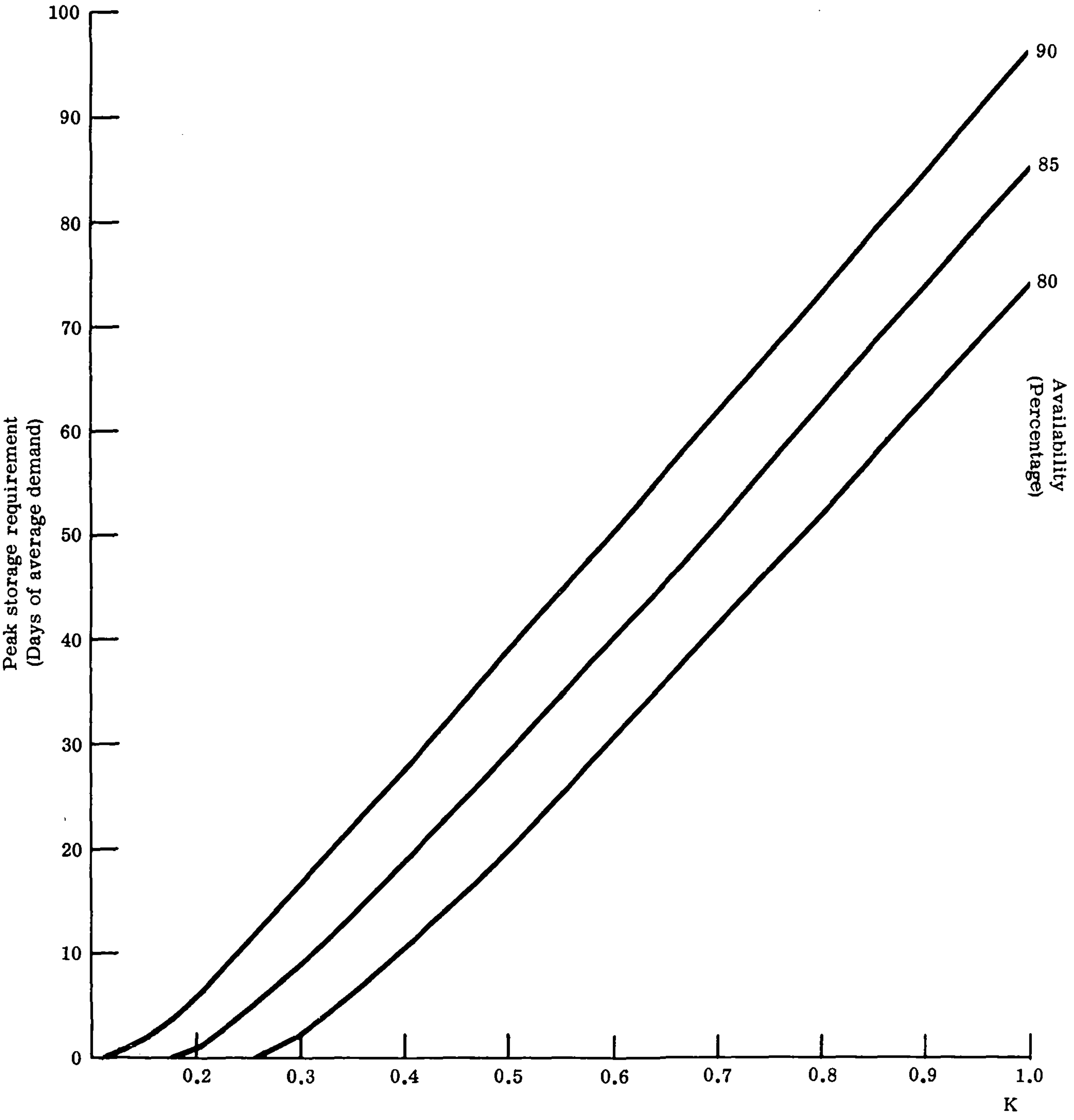

Figure IV. Peak storage requirement (minimum-size plant)

Demand and plant size as for figure III.

Table 3. Cost penalty of using minimum desalination capacity and peak storage as against peak desalination capacity and no peak storage (twin-plant installation)

(Cents/1,000 gallons)

A: Demand = 100 mg per annum
B: Demand = 365 mg per annum
C: Demand = 1,000 mg per annum

Plant availability (percentage)	Unit capital cost of storage (cents/gallon)	k[a] = 0.2			k[a] = 0.4			k[a] = 0.6			k[a] = 0.8			k[a] = 1.0		
		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
90	0 . .	-4.50	-3.16	-2.31	-14.1	-9.6	-7.16	-23.2	-15.9	-11.9	-32.0	-22.0	-16.4	-40.5	-22.9	-20.7
	1 . .	-3.2	-1.76	-1.01	-7.7	-3.2	-0.76	-11.6	-4.3	-0.34	-15.2	-5.2	+0.4	-18.4	-5.8	+1.4
	2 . .	-1.9	-0.46	+0.29	-1.3	+3.2	+5.64	-0.1	+7.2	+11.2	+1.6	+11.6	+17.2	+3.7	+16.3	+23.5
	3 . .	-0.6	+0.74	+1.59	+5.1	+9.6	+12.0	+11.5	+18.8	+22.8	+18.4	+28.4	+34.0	+25.7	+38.3	+45.5
	4 . .	+0.7	+2.04	+2.89	+11.5	+16.0	+18.4	+23.0	+30.3	+34.3	+35.2	+45.2	+50.8	+47.7	+60.3	+67.5
	5 . .	+2.0	+3.33	+4.19	+17.9	+22.4	+24.8	+34.5	+41.8	+45.8	+52.0	+62.0	+67.6	+69.7	+82.3	+89.5
85	0 . .	-1.31	-0.90	-0.67	-10.8	-7.43	-5.53	-20.0	-13.7	-10.2	-28.9	-19.9	-14.8	-37.4	-25.6	-19.1
	1 . .	-1.10	-0.69	-0.46	-6.5	-3.1	-1.2	-10.9	-4.6	-1.1	-14.5	-4.7	-0.4	-17.9	-6.1	+0.4
	2 . .	-0.88	-0.47	-0.24	-2.2	+1.2	+2.8	-1.8	+4.5	+8.0	-0.1	+9.7	+14.0	+1.6	+13.4	+19.9
	3 . .	-0.67	-0.26	-0.03	+2.1	+5.5	+7.4	+7.3	+13.6	+17.1	+14.3	+24.1	+28.4	+21.1	+32.9	+39.4
	4 . .	-0.46	-0.05	+0.18	+6.45	+9.8	+11.7	+16.4	+22.7	+26.2	+28.7	+38.5	+42.8	+40.6	+52.4	+58.9
	5 . .	-0.25	+0.16	+0.39	+10.8	+14.2	+16.1	+25.5	+31.8	+35.3	+43.1	+52.9	+57.2	+60.1	+71.9	+78.4
80	0 . .				-7.1	-4.87	-3.64	-16.3	-11.2	-8.4	-25.0	-17.3	-12.8	-33.7	-23.2	-17.3
	1 . .				-4.76	-2.53	-1.30	-9.4	-4.3	-1.5	-13.1	-5.4	-0.9	-16.8	-6.3	-0.4
	2 . .				-2.42	-0.19	+1.04	-2.5	+2.6	+5.4	-1.2	+6.5	+11.0	+0.2	+10.7	+16.6
	3 . .				-0.08	+2.15	+3.38	+4.4	+9.5	+12.3	+10.7	+18.4	+22.9	+17.1	+27.6	+33.5
	4 . .				+2.26	+4.49	+5.72	+11.3	+16.4	+19.2	+22.6	+30.3	+34.8	+34.0	+44.5	+50.4
	5 . .				+4.30	+6.53	+7.76	+18.2	+23.3	+26.1	+34.5	+42.4	+46.7	+51.0	+61.5	+67.4

Note: Negative cost entries indicate minimum desalination capacity is preferable. Positive entries indicate peak desalination capacity is preferable.

[a] For significance of variable k, see figure II.

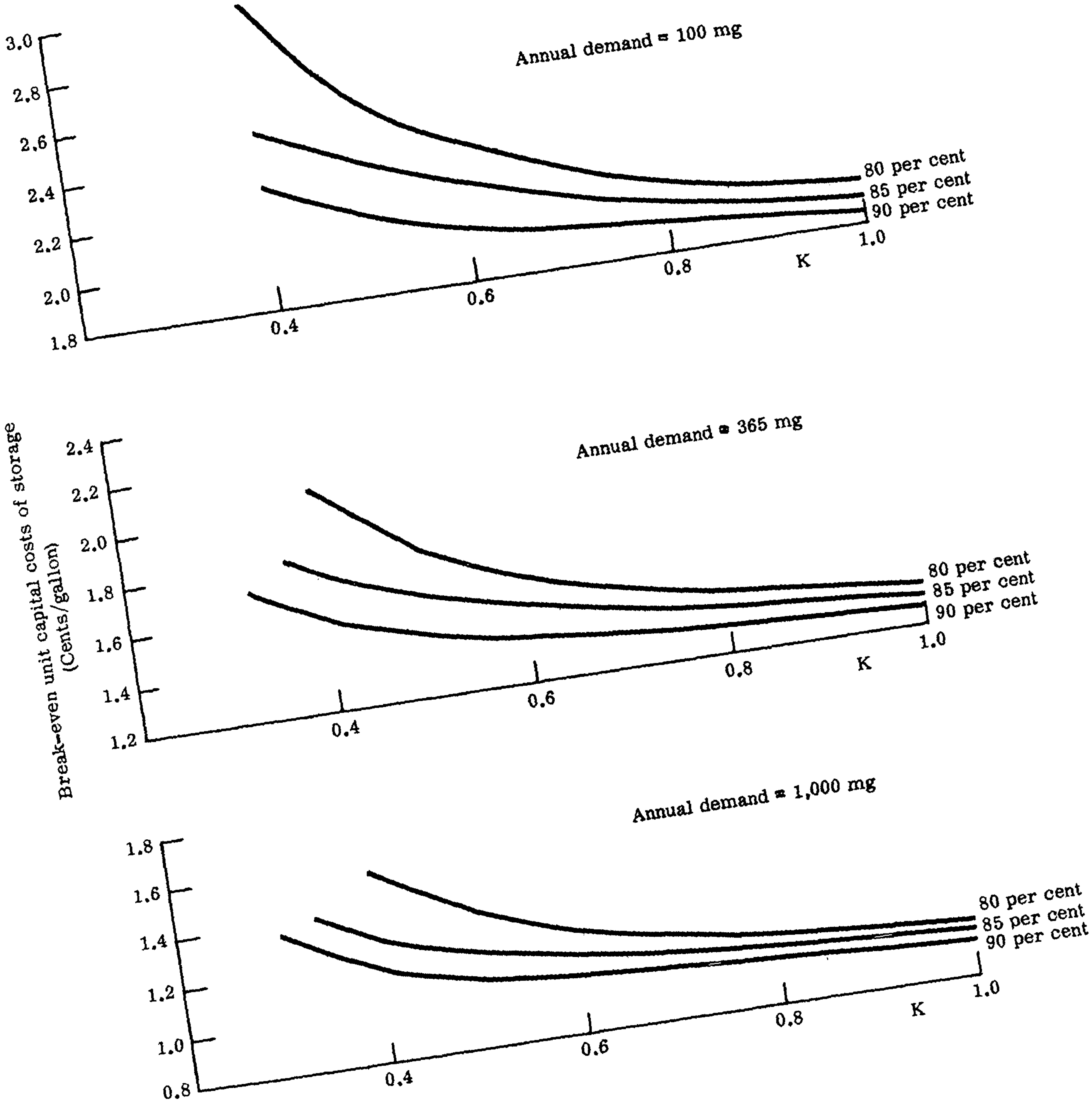

Figure V. Unit capital costs of sotrage at which costs of peak storage break even with costs of peak desalination capacity (twin units)

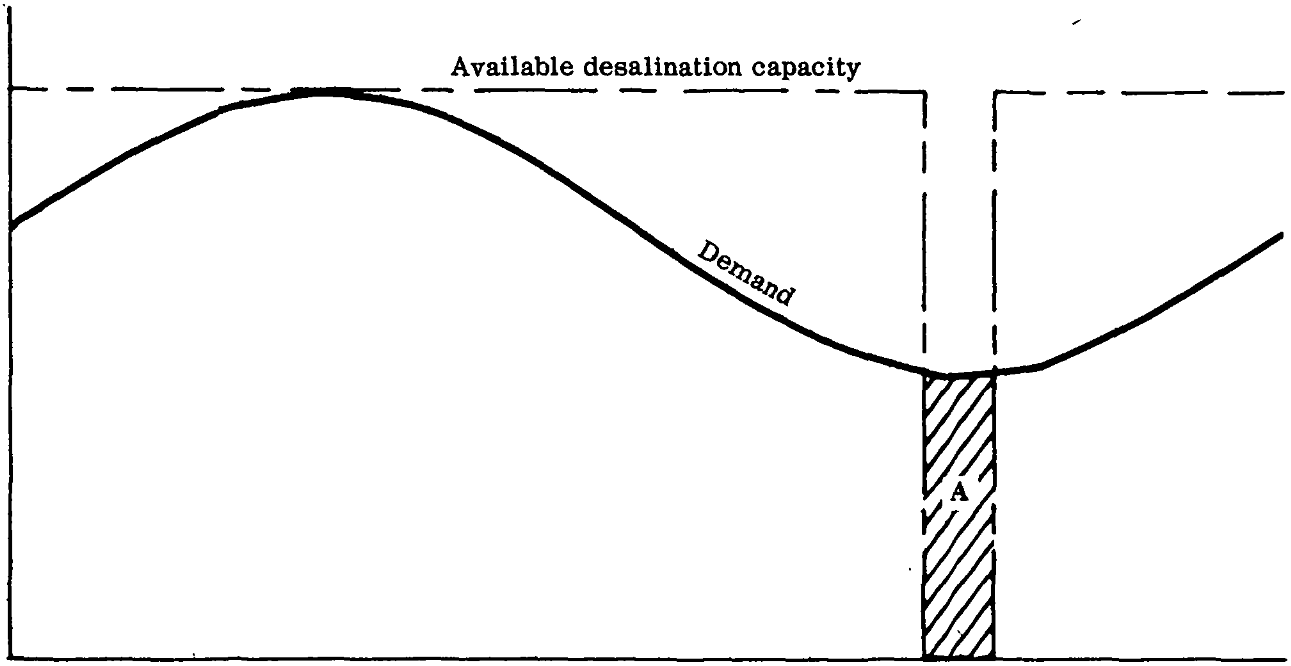

Figure VI. Storage requirement for scheduled maintenance (single Unit)

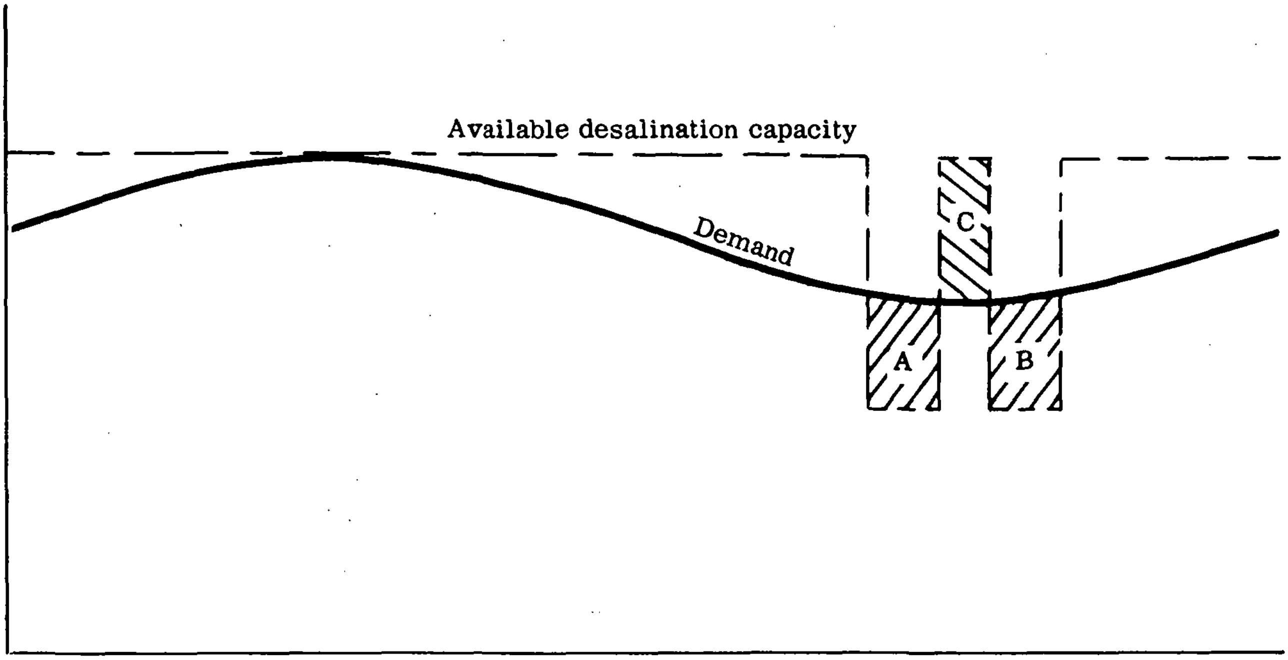

Figure VII. Storage requirement for scheduled maintenance (twin units)

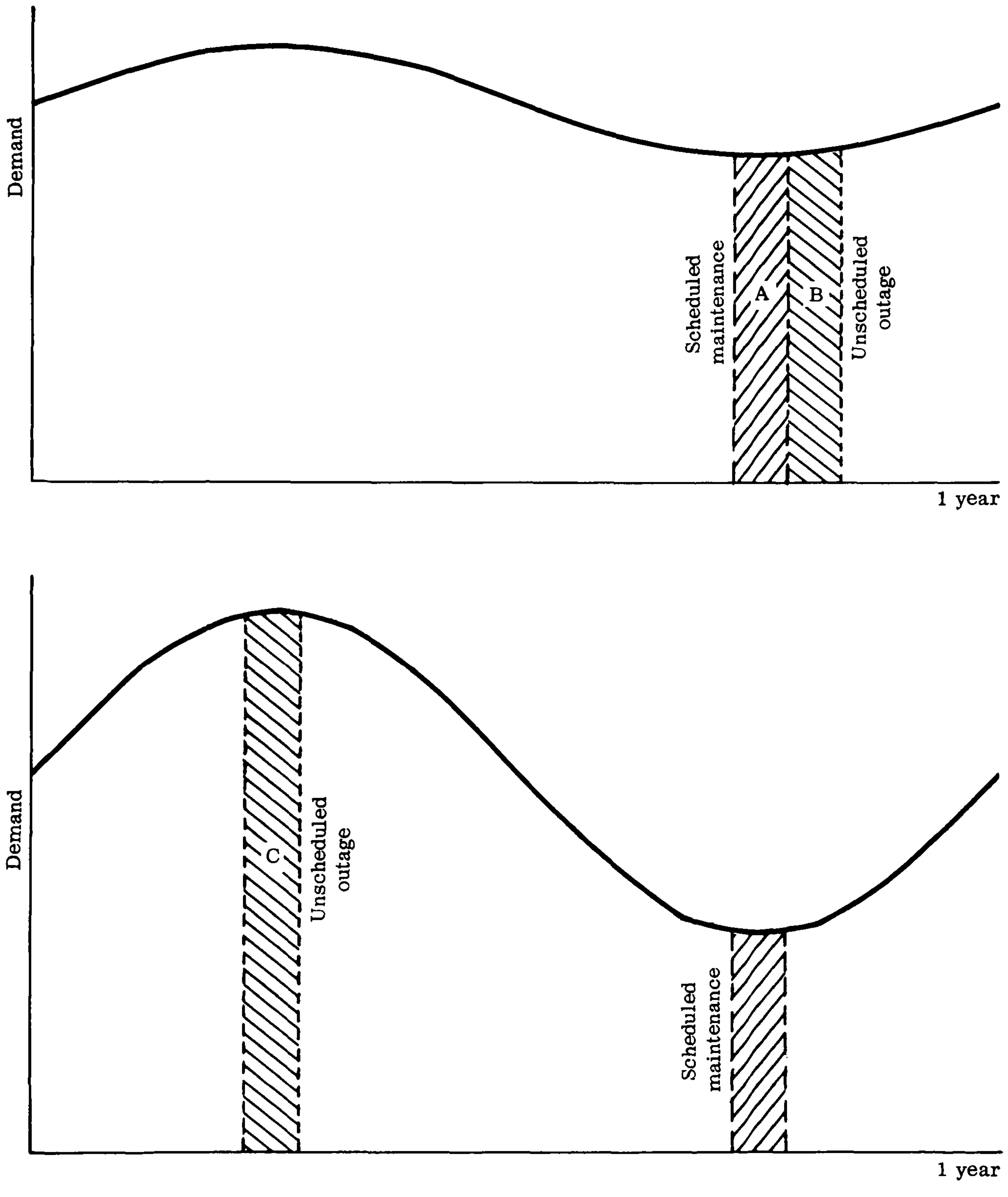

Figure VIII. Alternative configurations of scheduled and unscheduled outages resulting in the most critical storage requirement

Table 4. Storage requirements to cover plant outages
(Days of average demand)

k[a]	Q[b]	Storage to cover scheduled maintenance		Total storage to cover scheduled and unscheduled maintenance	
		Single unit	Twin units	Single unit	Twin units
0.1	10	18.9	7.4	27.9	16.4
	20			36.9	25.4
	30			45.9	34.4
0.2	10	16.8	4.2	24.8	12.2
	20			32.8	24
	30			40.8	36
0.3	10	14.7	1.1	21.7	13
	20			28.7	26
	30			39	39
0.4	10	12.6	0	18.6	14
	20			28	28
	30			42	42
0.5	10	10.5	0	15.5	15
	20			30	30
	30			45	45
0.6	10	8.4	0	16	16
	20			32	32
	30			48	48
0.8	10	4.2	0	18	18
	20			36	36
	30			54	54
1.0	10	0	0	20	20
	20			40	40
	30			60	60

---

[a] For significance of variable k, see figure II.
[b] Q is the duration of unscheduled outage.

Table 5. Additional water production cost incurred through installation of two half-size units as compared with a single full-sized unit

(Cents/1,000 gallons)

k[a]	Annual demand		
	100 mg	365 mg	1,000 mg
0.1	13.9 (61.0)[b]	9.5 (41.7)	7.1 (31.2)
0.2	14.8 (64.7)	10.1 (44.5)	7.6 (33.2)
0.3	15.7 (68.8)	10.7 (47.0)	8.0 (35.1)
0.4	16.5 (72.2)	11.3 (49.5)	8.5 (37.0)
0.5	17.3 (75.8)	11.8 (51.8)	8.9 (39.1)
0.6	18.1 (79.3)	12.4 (54.5)	9.3 (40.7)
0.8	19.7 (86.3)	13.5 (59.2)	10.1 (42.2)
1.0	21.1 (93.1)	14.6 (63.8)	10.9 (47.7)

---

[a] For significance of variable k, see figure II.

[b] Bracketed values are Xc, where X is the number of days of storage which must be saved to justify the additional water production cost of twin units, and c is the unit capital cost of storage (cents/gallon).

Example (using upper left-hand entry in table):

Additional water production cost of using twin units is 13.9 cents/1,000 gallons. Xc is shown equal to 61.0.

Say the local capital cost of storage facilities is 3 cents/gallon. Then for twin units to be justified it requires that the saving in storage requirements be at least equal to $\frac{61}{3} = 20\ 1/3$ days.

Table 6. Underground storage costs and equivalent units costs of surface storage facilities

k[a]	Maximum rate of recharge (mgd)	Capital cost (thousands of dollars)	Total transfer of water (mg/year)	Operating costs (thousands of dollars/ year)	Total cost (thousands of dollars/ year)	Equivalent unit cost of storage facility (cents/gallon)
0.4	1.09	24.1	51.7	0.465	2.875	0.067
0.6	1.64	36.2	109	0.982	4.602	0.050
0.8	2.19	48.2	173	1.56	6.38	0.044
1.0	2.74	60.3	234	2.10	8.13	0.042

Notes: Demand is assumed as D (1 + k sin x) where D = 2.74 mgd.

Plant availability is assumed 85 per cent.

Storage requirements are to meet seasonal peak in demand, as described in annex III.

[a] For significance of variable k, see figure II.

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