A Brief Survey of the Technology and Economics of Water Supply

James C. DeHaven, Linn A. Gore
and
Jack Hirshleifer

October 1953

Report R-258-RC
PREFACE

The RAND Corporation undertook this brief survey to delineate the problems of water supply and to indicate the more important areas for research in this field. This report records the findings of several of our staff — engineers and an economist — who made the study. The survey was originally planned for internal use to explore the possibilities for research in the field by the varied professional talents available at RAND. The somewhat unusual approach to the subject, with greater emphasis than usual on the economics of water, has led us to believe that this report may be of sufficient interest to warrant more widespread distribution. It is therefore added to the other RAND publications on matters of national interest.

This report is not to be viewed as a basic contribution to our knowledge, but rather as a means of bringing together a body of information which we hope will be informative and may encourage others to undertake research in useful directions.

F. R. Collbohm
Director
The RAND Corporation
INTRODUCTION

News reports of wells drying up, reservoir levels falling, and water use being placed under restriction in various areas all lead to a widespread popular belief that our consumption of water is dangerously depleting the supply. Many people fear that unless something drastic is done about the situation we may face curtailment of the industrial and agricultural growth of the nation, especially in the drier areas in the West where industry and population have expanded so rapidly during the past decade. In view of this apparent increasing deficiency of fresh water it is natural to look toward the oceans as potential sources, as well as to consider alternative means of increasing or conserving water supplies. The present report is a survey of the technological and economic facts governing water supplies and demands, both actual and potential.

As so frequently happens, facts and sober analysis largely dissipate fears. Water is an economic resource, like any other. It will never be "short" in any absolute sense, since there is always more available—at a price. It is true that water stringency may limit growth of an area, but only in the same sense in which the limited availability of any resource may be a check upon growth. If a certain region ceases its expansion relative to the rest of the nation or the world for lack of easily available water, it means only that the natural advantages, of which the availability of water is one example, of that region have been utilized to their economic limit. The situation differs in no essential respect from instances in history in which a period of rapid relative growth of one region or another came to an end as the supply of such resources as land or coal was pressed to its economic limit.

With this general point of view, it is still of interest to examine the future prospects for water supply. Will water in the near future become so scarce that it will in fact be a severely limiting factor upon regional and national growth, or can present use be greatly expanded
without driving up the cost to unprecedented heights? Furthermore, granted that increased supplies can in general be purchased only at increased cost, what sources of the desired increments of water will be the most economical and should be exploited first? These are the questions our study is designed to answer.

Our approach to the problem begins with an examination of the hydrologic cycle to provide a background for assessing the total natural water available to our nation and its distribution by source. The pattern of water supplies and requirements in the Los Angeles region — an area where the availability of water has been of popular concern for many years — is used as the context in which to compare the feasibility and economic advantages of the various sources of additional fresh water.

Next, we examine the theoretical aspects and estimate the present and future costs of producing fresh water from saline by known technically feasible processes. Other measures which may either conserve or expand the natural water resources are explored in order to compare their costs and feasibility with those of methods for obtaining useful water from the sea.

The results of our study indicate that, even with substantial allowance for major engineering improvements, salt water conversion processes will not generally compete in the foreseeable future with water from natural sources or with water made available by reclamation, reallocation, conservation, and more rational pricing practices — all of which we discuss. Sea water conversion appears to be economical in the future only in some isolated parts of the world where water supplies are exceptionally limited. A possible exception to this generalization may be regions with substantial supplies of brackish (semisalt) water.

JAMES C. DE HAVEN
LINN A. GORE
J. HIRSHLEIFER
CONTENTS

PREFACE ............................................................ iii

INTRODUCTION ..................................................... v

THE HYDROLOGIC CYCLE ........................................ 1
  From Ocean to Atmosphere .................................... 2
  Water Vapor in the Atmosphere ............................... 3
  Water in the Land Portions of the Hydrologic Cycle ... 4

THE SUPPLY OF NATURAL FRESH WATER VERSUS THE REQUIREMENTS ... 9

THE MANUFACTURE OF FRESH WATER FROM THE SEA ........ 17
  The Thermodynamics of Salt and Water Separation ........... 18
  Description and Costs of Fresh Water Manufacturing Processes ............................................. 20
  Estimated Costs of Manufacturing Fresh Water from Saline ...................................................... 29

METHODS OTHER THAN SALINE WATER CONVERSION FOR INCREASING SUPPLIES OF WATER .................... 35
  Conserving Supplies of Natural Water ......................... 35
  Assisting Nature To Increase Present Natural Water Supplies ...................................................... 41
  The Direct Use of Sea Water .................................. 44

CONCLUSIONS ...................................................... 47

BIBLIOGRAPHY ..................................................... 49
THE HYDROLOGIC CYCLE

Water seldom stays put for very long in nature. The stylized drawing in Fig. 1 represents some of the paths water follows between oceans and continents. Evaporated from the oceans by solar energy, water in a vapor state may be transported long distances in the earth's atmosphere. Varying conditions of atmosphere flow rates, and differences of energy inputs from above the atmosphere and from the surfaces below, cause concentrations of water vapor to increase or decrease in the flowing atmosphere. Where these conditions are such that increased concentrations are obtained and temperatures are lowered, clouds of different

*No attempt will be made in this brief survey to relate each item mentioned to a specific literature reference. A bibliography of the literature consulted is included on p. 49.
configurations and at different altitudes are produced. Clouds are composed of condensed water or ice particles. When certain additional and incompletely known conditions of temperature, degree of saturation, and concentration of nuclei are reached, the cloud particles may grow in size and drop to the surface of the earth as rain, snow, or hail. Under other conditions, the cloud particles may re-evaporate into the atmosphere, and the clouds disappear.

A number of things may happen to the water which falls to the earth:

1. It may almost immediately re-evaporate into the atmosphere.
2. It may soak into the earth or fall upon oceans, lakes, or streams, and later be directly evaporated or go through the life cycle of plants and pass to the atmosphere from the foliage (evapotranspiration).
3. It may fall as snow on cold mountains to be stored on the surface until the next thaw, at which time it enters land portions of the hydrologic cycle.
4. It may percolate through surface soil to enter underground porous beds or strata which serve as underground reservoirs (aquifers).
5. It may run off the soil surface to enter streams and rivers.
6. It may be entrapped as ice in polar icecaps or in glaciers.

In the first two instances, the evaporation of precipitation causes the water to re-enter the flowing atmosphere and to become unavailable for use. In the last-named instances, the water enters phases of the dynamic hydrologic cycle in which it becomes, in varying degree, available for man's use in the liquid state before returning again to the atmosphere or to the oceans. Knowledge of many of the important features of this entire cycle is incomplete. However, some understanding of the important relationships which appear to exist within this cycle may be gained by a brief review of the present knowledge of the subject.

From Ocean to Atmosphere

The oceans cover more than 70 per cent of the earth's surface. Therefore, they receive the major portion of the energy radiated by the
sun on the earth. The atmosphere does attenuate and absorb some energy directly as radiation passes through it to the earth's surface. The amount of energy absorbed varies with the amount of water vapor present and with the scattering effect of dust particles. Of the total solar energy absorbed at the sea surface during a year, approximately 50 per cent is used for evaporating sea water. Therefore, this energy is made available to the atmosphere in the form of latent heat of evaporation of water vapor. This constitutes the most important component of the atmospheric heat budget.

There are certain areas on the ocean's surface where the amount of evaporation is high, some where it is low, and, at certain times of the year, some areas where it is negative. The areas of high and low evaporation seem to coincide with permanent high and low atmospheric pressure areas; this may be important in determining weather patterns.

Variation, over time, in the energy radiated from the sun has not been precisely measured throughout a wide frequency range. There is evidence to indicate that large variations occur in radiation in the ultraviolet and far ultraviolet regions. These variations appear to be related to sunspot maxima and minima. One of the working hypotheses regarding long-term and short-term variations in the earth's climate relates these changes to changes in solar radiation in this portion of the spectrum.

The pattern of circulation of the earth's atmosphere, which determines our weather, is constantly changing. The fluctuations appear to occur in an almost continuous spectrum of periods varying in frequency from time measured in geological epochs to time measured in hours. Although the science of long-range forecasting is extremely new and not well developed, the indications are that there is a long-run tendency for the midlatitudes to become drier.

Water Vapor in the Atmosphere

It has been estimated (1933) that for each square centimeter of the earth's total surface there are 273 liters of water distributed as follows:
A SURVEY OF WATER SUPPLY

<table>
<thead>
<tr>
<th>Source</th>
<th>Amount (in liters)</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea water</td>
<td>268.45</td>
<td>98.33%</td>
</tr>
<tr>
<td>Fresh water</td>
<td>0.1</td>
<td>0.036%</td>
</tr>
<tr>
<td>Continental ice</td>
<td>4.5</td>
<td>1.64%</td>
</tr>
<tr>
<td>Water vapor</td>
<td>0.003</td>
<td>0.0011%</td>
</tr>
</tbody>
</table>

These must not be thought of as static quantities, but as representative of concentrations in the dynamic hydrologic cycle. The amounts in each category will vary slightly with seasons and to a more marked degree with the major climatic fluctuations described in the previous section. The amount of water present as vapor in the atmosphere at any one time seems small compared with the amounts distributed elsewhere. However, this water can be considered as being in transit. When it is decreased by precipitation, more will be evaporated to take its place. Also, when it is recalled that each gram of water in the vapor state represents a heat content 540 calories larger than 1 gm of liquid water at the same temperature, the greater import of the water vapor in the heat budget of the atmosphere can be appreciated. The vital importance of water acting as a thermal buffer against changes in energy received on the earth's surface cannot be overemphasized. Without this buffer action — provided by different phases of the hydrologic cycle — life as we know it would not exist. The temperature extremes even between day and night would be too great for present plants and animals to thrive in. By providing long-term large heat sources and heat sinks, the oceans and continental ice also damp the large climatic fluctuations.

Atmospheric water vapor is not uniformly distributed through the earth's atmosphere, but is concentrated and may condense and precipitate. During localized concentration and precipitation, very large energy exchanges take place within the atmosphere. It is estimated, for example, that one thunderstorm over Ohio (a large coal-producing state) releases more energy than is produced by all of the coal mined in the state during the year.

**Water in the Land Portions of the Hydrologic Cycle**

We have already seen that precipitation may follow any of a half-dozen courses. An attempt will be made here to summarize the import
THE HYDROLOGIC CYCLE

of the different land phases of the hydrologic cycle. It is this portion of the cycle from which we obtain our present natural fresh water.

Surprisingly enough, water which is present in springs, streams, rivers, and lakes represents surplus water, and in toto, is a small portion of the water available on the land masses. Generally speaking, in areas having over 20 in. of annual rainfall, such as the eastern half of the United States, the water which percolates to the porous underground strata, called aquifers, represents by far the largest amount of available fresh water. Surface water is either the overflow from aquifers or water that has failed to reach them.

In the western portions of the United States, where annual average precipitation is generally less than 20 in., the snow pack on mountains represents the most important source of fresh water. Much of this water reaches the aquifers and is subsequently pumped from wells for use. The important difference is, however, that the western ground water basins, or aquifers, are not generally charged directly by percolated precipitation as in the more moist climates, but by runoff water from melting mountain snow.

We are just beginning to learn something about these important underground aquifers. Their total capacity and extent are not accurately known, although surveys of them are under way in localized areas. California leads all other states in the percentage of water used which is pumped from aquifers. This does not mean that water is scarcer relative to demand in California than elsewhere, but rather that the knowledge of proper water management has probably reached a higher level than in most other areas of the country. The trend even in the eastern states is now toward a greater use of underground waters.

Water does not usually remain stationary in the aquifers, but flows from the charging areas either to areas of natural discharge, such as springs, swamps, ponds, and lakes, or to wells. (Charging areas are those specific land areas whose characteristics permit water to percolate down to the aquifer.) Water has been known to move 300 miles or more in these underground strata, although the usual distances range

---

*The so-called connate waters are an exception. These underground waters, usually too saline for use, were trapped and sealed by geologic processes.
from 5 to 100 miles. The lowering of the water level in an aquifer through well pumping does not necessarily mean that the water supply is being overdrawn. On the contrary, such a local lowering of the water level often causes increased flow through the strata and decreased wasteful runoff in the charging and discharging areas. Of course, if the local lowering reduces the hydraulic level much below sea level in coastal areas, there may be danger of contaminating fresh water with saline water. This is especially true if impenetrable strata covering the aquifer have been pierced near the sea by artificial harbors, abandoned wells, etc. Even without such penetration, contamination may occur because in coastal areas there may be hydraulic continuity of fresh water bodies and marine water without barriers between them.

In some areas the natural aquifers are being recharged synthetically through spreading-beds in porous recharge areas or through wells. The water used for recharging may be excess runoff water, imported water (e.g., in the Los Angeles area, from the Colorado River), drainage from irrigation, suitable industrial discharge water, or the discharge from sewage disposal plants.

The use of aquifers in this manner has many advantages. They are natural reservoirs, available without construction cost and at low operational cost. They provide very large storage capacity where excessive supplies of water in moist years may be stored to extend supplies in dry years. Water so stored is not subjected to the very high evaporative loss rates of above-ground reservoirs. Aquifers are natural "pipelines" through which water may be transported from moist charging areas to drier areas for only the low cost of pumping. Of course, care must be taken in recharging to avoid contamination of the aquifer with too much high-salinity irrigation discharge water or with unhealthful industrial or sewage discharges. Care must also be taken that charging areas are not blocked by construction over them or by washed-in non-porous material.

The completion of the hydrologic cycle occurs when the water precipitated on the ground returns to the sea in rivers or from sewage outlets. With the proper husbandry of water it might be postulated that this return should consist only of water so high in dissolved solids con-
tent that it is unusable for any of man's purposes without some treatment which would be more costly than the price of the next available increment of natural water.

There is an important short circuit in the hydrologic cycle which is beginning to receive more attention. This is the evaporation of water from reservoirs, aqueducts, lakes, and soil to the atmosphere. More accurate measurements of this loss are now being attempted.
THE SUPPLY OF NATURAL FRESH WATER VERSUS THE REQUIREMENTS

During the past forty years precipitation over the United States has averaged 30 in. or a total of 15,648,000 billion gal per year. It is estimated that the current water demand for irrigation, industrial, and public supplies in the United States is at the rate of 200 billion gal a day, or 75,000 billion gal a year. Some of this demand is met by water which is reused several times. So, we are actually using for these purposes less than one-half of 1 per cent of the water received. Even when evapotranspiration loss through beneficial and nonbeneficial vegetation is deducted from the available supply of water, the use of water for irrigation, industrial, and public supplies represents less than 1.7 per cent of the remaining water received as precipitation.

It is obvious, then, that the problem in the United States is not one of absolute water shortage. For each area the problem is to determine the lowest-cost method for obtaining the next incremental amount of water for expanding requirements. Instead of talking about shortages, we should consider the pattern of water supply and demand at various prices.

The South Coastal Basin of California has been selected as an interesting area for examination. It is close to the ocean, has shown an increasing demand for water, and has been used as an example of an area where salt water conversion might relieve a “water shortage.” This basin, which includes the metropolitan Los Angeles area, contains approximately half the state’s population, 10 per cent of its irrigable lands, and has less than 1.5 per cent of the state’s natural water supply.

The area (the South Coastal Basin consists of Los Angeles, Orange, Riverside, and San Bernardino Counties) is underlain by aquifers which are charged naturally by runoff from the mountains to the north and east. These aquifers are the source of essentially all the natural local water supply. It was recognized very early in the area’s history as a
metropolitan center that the local supply would be inadequate for future growth. So, more distant supplies were tapped — first, by the aqueduct to the Owens River (later extended to the Mono Basin), and subsequently by the huge aqueduct project to the Colorado River.

So far as is known, there is not presently available an integrated statement of the current demand and supply or the estimated future demand and supply of water for this area. It has been possible, however, to piece together some estimates from several sources, primarily from personal communications with responsible individuals familiar with the water supply problems of the Southern California region. For this reason, few citations can be given to published material.

In recent years, approximately 980,000 acre-feet\(^*\) a year of local runoff and ground water were used in the South Coastal Basin. Most of this water is pumped from wells and is used mainly for irrigation, although some of the municipalities in the area tap the aquifer for their supply. This rate of draft is about 250,000 acre-feet a year beyond the capacity of the aquifer; water levels have been consistently falling for a number of years. The water level is now largely below sea level, in some areas as much as 70 ft below, and serious problems are arising with salt water intrusion up to 2 miles in from the coast.

We must remember that this water is the natural source for the area. It is “free” to anyone who wishes to drill a well and tap it. The only costs are those for drilling, for buying and maintaining pumps, and for the power for pumping. This water may cost around $5 per acre-foot\(^*\) compared with imported water costing from $10 to $20 per acre-foot wholesale (typically still higher for the individual consumer). It is only natural that a loud clamor about water shortages should be raised by those who are using $5 water and who see it gradually disappearing.

\(^{*}\) Quantities, flow rates, and costs of water are stated in several different ways: in thousands of gallons, in millions of gallons, in acre-feet (1 acre-foot = 325,851 gal), or in cubic feet. Flow rates in the above terms may be stated per second, per minute, per day, or per year. A draft of 10,000 acre-feet per year is about equal to 9 million gal per day and requires a continuous discharge of about 14 cu ft per second.

\(^{†}\) The figures $1.50 to $6.00 an acre-foot are widely quoted as the costs for well water. However, with the increasing cost of equipment and greater depth of wells, it is probable that even the highest figure does not represent the present actual cost of well water in the area.
from under them. They have other sources of water, as will be seen, but the cost will be two to four times that of their present supply. There is no additional supply of natural cheap water in sight.

The Los Angeles Aqueduct from the Owens Valley was completed in 1913. It has a capacity of 400 cu ft per second (about 320,000 acre-feet per year). For many years excess winter flow from this system was stored in the aquifer under the San Fernando Valley to be used during the summer peak demand periods. In recent years, however, year-round demand has grown to absorb the full capacity of the aqueduct. No surplus exists for storage.

Since 1941, the Metropolitan Water District of Southern California, through the Colorado River Aqueduct, has been supplying a gradually increasing amount of water to the area. In fiscal 1951–1952 this amounted to 150,000 acre-feet. This amount, plus approximately 320,000 acre-feet from the Owens River, plus approximately 980,000 acre-feet from local ground water draft, gives a total of about 1,450,000 acre-feet as the annual water consumption of the area. The Metropolitan Water District has contracts for an annual draft of about 1,050,000 acre-feet per year from the Colorado River for the South Coastal Basin. The aqueduct was constructed to handle this volume, but current demand is only a fraction of the capacity of this source. The remaining 900,000 acre-feet per year is sufficient to allow more than a 50 per cent increase in the current water use in the area.*

The Division of Water Resources of the California State Department of Public Works has suggested a system to meet future potential demands by bringing water from the Feather River watershed north of Sacramento, where there is excess supply, to as far south as the Mexican

---

* Litigation between the states of California and Arizona over interpretation of the agreements concerning the allocation of water in the lower Colorado Basin has been taken to the Supreme Court. California claims about 5,400,000 acre-feet annually, while Arizona says California’s share is about 3,900,000 acre-feet. California allocates its share to irrigation districts around Palos Verde, Yuma, and Imperial and Coachella Valleys, in addition to the Metropolitan Water District. Should Arizona’s claims be upheld in full, existing priorities for uses within California are such that little or no additional water would be available for the South Coastal Basin. It is reasonable to believe, however, that such an unexpected development would lead to a readjustment of priorities so as to provide for a more reasonable distribution of the loss. The results of all litigation to date have been adverse to Arizona.
border. This project would be entirely independent of the Central Valley project, which is largely a Federal undertaking. The proposed project would provide a capacity of about 3,600,000 acre-feet per year of which about one-fourth might be scheduled for the South Coastal Basin.

Responsible proposals are also being made for the use of properly reclaimed water from sewage to supplement the future supply. It is noteworthy that the discharge of water in sewage from the city of Los Angeles and Los Angeles County now exceeds the supply of water from the Owens River Aqueduct. It is proposed that water-reclaiming plants be constructed which are completely separate from the regular sewage disposal plants. These plants would take as their input sewage from domestic and industrial sewer lines either upstream or downstream from the regular sewage plants. Their fresh water output could be used directly in irrigation or by industry, or used to recharge the underground aquifers. Most of the know-how is available to make this system work; it is already in use in one form or another in many areas of the country. Additional research is necessary to determine the degree of treatment required for direct irrigation purposes, and more knowledge is needed about the mechanism of charging large quantities of reclaimed water into aquifers. However, this system represents a source of about 400,000 acre-feet per year, based on 1950 rates of sewage flow in the South Coastal Basin, and an additional potential source of perhaps 1,000,000 acre-feet per year as more imported water is brought into the area.

The estimates of present and future natural water supply and costs for California's South Coastal Basin are summarized in Table 1.

There is no generally acceptable method of approximating the potential demand for water. However, Table 2 shows the past population growth for the Southern California Coastal Area.

The amount of water needed in Southern California has in the past been closely related to the phenomenal population growth which has taken place in the area, and projections for the future will also presumably be dominated by this factor. Demand for water is also influenced by industrial and residential patterns in the area, the level of business activity, and of course the price of water itself. Nevertheless, the per capita use of water apparently remained surprisingly constant
## Table 1

**ESTIMATED PRESENT USE AND POTENTIAL SUPPLY OF WATER — SOUTH COASTAL BASIN OF CALIFORNIA**

<table>
<thead>
<tr>
<th>Water Source</th>
<th>Present Use (acre-feet per year)</th>
<th>Potential Supply (acre-feet per year)</th>
<th>Approximate Cost per Acre-foot ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local runoff and ground water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safe yield (estimated)</td>
<td>730,000</td>
<td>730,000</td>
<td>4.50–6.00d</td>
</tr>
<tr>
<td>Present overdraft</td>
<td>250,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Owens River</td>
<td>520,000</td>
<td>320,000</td>
<td>19.00</td>
</tr>
<tr>
<td>Colorado River Aqueduct</td>
<td>150,000</td>
<td>1,050,000</td>
<td>10.00b</td>
</tr>
<tr>
<td>Reclaimed water</td>
<td></td>
<td></td>
<td>20.00 (softened)</td>
</tr>
<tr>
<td>Present potential</td>
<td></td>
<td>400,000</td>
<td></td>
</tr>
<tr>
<td>Future added potential</td>
<td></td>
<td>(1,000,000)</td>
<td>30.00–35.00</td>
</tr>
<tr>
<td>Feather River</td>
<td></td>
<td>850,000</td>
<td>50.00–100.00c</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>1,450,000</strong></td>
<td><strong>4,330,000</strong></td>
<td></td>
</tr>
</tbody>
</table>

a Although these figures are generally quoted in the area, they often do not fully reflect the proper allowance for interest on the investment and depreciation. The cost of local ground water pumpage may increase substantially in near future years with increased pump lifts, the deepening of wells, and increased cost for replacement of motors, pumps, etc.

b These prices for Metropolitan Water District supplies do not cover the full cost of the water, since the District must also levy a tax on assessed valuation throughout its area to balance its budget. The prices are roughly comparable, however, with the District’s operating cost for delivering additional water. Since the aqueduct is already in place, and the fixed costs must be covered whether the water is used or not, these prices do roughly represent the true additional cost to the community of water deliveries, which is what is shown in the table.

c The $50 estimate is based on the assumption of operation at 100 per cent capacity from the first month. On a perhaps more realistic load-building and load-factor basis, the Feather River costs may be closer to the $100 figure, or perhaps even higher.

## Table 2

<table>
<thead>
<tr>
<th>Year</th>
<th>Population</th>
</tr>
</thead>
<tbody>
<tr>
<td>1890</td>
<td>175,000</td>
</tr>
<tr>
<td>1900</td>
<td>270,000</td>
</tr>
<tr>
<td>1910</td>
<td>677,000</td>
</tr>
<tr>
<td>1920</td>
<td>1,208,000</td>
</tr>
<tr>
<td>1930</td>
<td>2,720,000</td>
</tr>
<tr>
<td>1940</td>
<td>3,408,000</td>
</tr>
<tr>
<td>1950</td>
<td>5,250,000</td>
</tr>
<tr>
<td>1952 (estimated)</td>
<td>5,650,000</td>
</tr>
</tbody>
</table>
between 1928 and 1950.* Between 1930 and 1950, then, total water use kept pace with total population, each just about doubling. Barring a radical increase in the rate of growth of the region, the potential supply (through the $50 to $100 cost range) of approximately three times the current use may be considered adequate for quite a long period in the future, especially as the increasing price of water may slow any tendency toward increasing water use per person.

There are, furthermore, additional potential sources of natural water not included in our table of supplies, but which may substantially affect the over-all situation:

1. **Extension of supplies by prevention of evaporation.** This might be achieved by, for example, an oil layer over reservoirs. It is believed that any such saving might be accomplished at less expense than the cost of the next equivalent incremental supply from other sources. The magnitudes involved are not yet known. In addition, some of the possible techniques for preventing evaporation may interfere with other uses of water.

2. **Purchase of other regions’ water allocations.** While the Southern California Coastal region has a Colorado River allocation of about 1,050,000 acre-feet, the Imperial Valley and adjacent areas have allocations of about 4,150,000 acre-feet, and other areas have residual claims. Essentially all the water for these other areas goes into low-value agricultural uses. It therefore appears quite possible that by the time the Los Angeles region is paying $50 per acre-foot for water, it may be able to make an attractive offer to buy at a mutually satisfactory price some portion of the allocations of these other areas. The magnitudes involved are of such importance as to warrant giving serious thought to redistribution before constructing expensive facilities to augment supplies in other ways.

---

3. Impounding of additional runoff water. In the specific area considered this may be limited by the availability of suitable dam sites and the high costs of land for impounding reservoirs. However, in other areas this practice has not been fully exploited and may represent the technique which will provide the cheapest additional source of water.
THE MANUFACTURE OF FRESH WATER FROM THE SEA

We have seen how all of our natural fresh water is evaporated from the sea by the sun, enters the flowing atmosphere, and subsequently is precipitated on the land masses. Proposals are often made to short-circuit the natural hydrologic cycle by manufacturing fresh water directly from the sea. This procedure is completely feasible technically. For hundreds of years ships at sea have obtained fresh water by distillation of salt water. The major question to be examined is whether fresh water can be manufactured by any method which will compete economically with water from natural sources.

Some forty-nine elements are known to exist in sea water. However, many of them are present in such small quantities that they may be tolerated in the majority of uses for fresh water. The largest concentrations are of chlorine, sodium, magnesium, sulphur, calcium, and potassium. These occur in ionic form and represent a total dissolved solids content of about 35,000 parts per million (ppm) of water. Of course, this concentration varies somewhat throughout the ocean areas, depending on rate of evaporation, local dilution by large fresh water outlets, etc. There are certain inland sources of water having lower solids content. These waters are called brackish and may range from 1500 to 10,000 ppm of dissolved solids. It is usually best to have solids below 1000 ppm for human consumption and below 500 ppm for agricultural uses, plants being more sensitive than human beings to certain elements. However, these allowable concentrations may vary up or down depending on the elements present. Sodium and boron are especially undesirable.

It is perhaps unnecessary to point out that there are just two basic ways to manufacture fresh water from saline — either to remove the water from the salts, or the salts from the water. It will be shown in the next section that these two methods require the same theoretical
minimum of energy per unit of water produced. These two procedures serve as convenient slots to characterize the numerous techniques used and proposed for producing fresh water from saline.

The Thermodynamics of Salt and Water Separation

Any process for producing pure water from sea water will consume power at a rate corresponding to the theoretical energy required to separate the salt from the water, plus the energy lost in friction, heat losses, etc. The frictional and heat losses depend on the method of purification used and on the design of the associated machinery. However, the theoretical minimum energy required to purify sea water can be calculated from well-known thermodynamic principles, and the result is independent of the method of purification used.

The average salinity of ocean water is about 35 gm of solids per kilogram of sea water. It can be shown that the minimum power required for separation is 2.6 kilowatt-hours (kw-hr) per thousand gallons yield of pure water.* This figure represents the power required to separate the first fraction of pure water from a given batch of sea water. If the separation is carried further, the power required will rise as the yield per gallon of sea water is increased. To separate half of the water from sea water requires about 40 per cent more power for the same yield, or 3.6 kw-hr per 1000 gal, while to perform a complete separation into pure water and dry salt requires a theoretical minimum of about 9 kw-hr per 1000 gal. (This last value was estimated from the properties of pure sodium chloride solutions, since data on actual sea water could not be found.)

From a strictly theoretical standpoint, it appears that the most efficient separation process would use many gallons of sea water for each gallon of fresh water produced, returning the slightly saltier residue brine to the ocean. Actually, however, a plant using such a process

*This value should be increased up to 5 per cent for equatorial ocean waters, decreased by 5 per cent for polar waters, and also increased about 1 per cent for each 5°F temperature rise. In salt-water seas (as distinguished from larger oceans) the variation is considerably greater. For example, purification of water from the Mediterranean requires 10 to 15 per cent more power than the average value quoted above.
would have to be much larger physically than one with equal output
which separated a larger fraction of the water from sea water. The
extra pumping expenses, heat losses, and amortization of the larger
capital investment could easily amount to many times the theoretical
power savings, so some compromise must be struck. Modern compres-
sion-distillation plants separate about 80 per cent of the water from
sea water.

The distinction made between processes which remove the water from
the brine and processes which remove the salt from the brine is not
significant from a thermodynamic standpoint. Disregarding losses, the
theoretical power required for separation is determined entirely by the
amount and quality of the salt water processed and the fraction of pure
water which is removed from it. Unfortunately, however, these heat
and friction losses make up 90 to 99 per cent of the power costs of
operating any presently designed water purification system. Thus, the
distinction between water removal and salt removal does have a prac-
tical significance, as will be shown.

In a distillation process, a large amount of heat (about 2500 kw-hr
per 1000 gal) must be supplied to evaporate the water. Theoretically,
all of this heat — except the 2.6 kw-hr per 1000 gal separation energy
— can be recovered when the pure water condenses and then reused
to heat the incoming salt water. Because of practical limitations on heat
exchangers, an appreciable fraction of the 2500 kw-hr per 1000 gal is
lost, and thus the actual process requires many times the theoretical
amount of power. It is to be noted, too, that the losses are almost
independent of the salt concentration. Because of these losses, the puri-
fication (by distillation) of brackish water containing only one-tenth
as much salt as sea water — for which the theoretical power required is
0.26 kw-hr per 1000 gal — actually requires almost as much power as
the purification of sea water. In contrast, the energy losses in an ion-
exchange process (see below) of purification may not be so large.
(However, the energy for separation in some ion-exchange processes is
supplied by expensive chemical energy — 100 lb of concentrated acid
or base yielding the equivalent of only 1 or 2 kw-hr.) Thus, costs of
processes which remove salt from water are more directly related to
the salt concentration. Such processes therefore tend to have an advantage over distillation when brackish water is being used, distillation becoming relatively more profitable when sea water is being used.

**Description and Costs of Fresh Water Manufacturing Processes**

**DISTILLATION SYSTEMS**

Of those methods which remove water from salt, distillation in one form or another is the most advanced from the practical point of view. Figure 2 illustrates four different distillation systems which will be described. Almost every American naval vessel uses distillation to provide potable water at sea. During World War II, large distillation units were set up on arid islands to provide water for military use.

**Multiple-effect Evaporators**

There have been several large units set up recently in isolated places such as Persia to supply fresh water from the sea for petroleum refinery operations. The Persian unit, the largest in the world, supplies 720,000 gal of fresh water a day. It is a multiple-effect evaporator designed to recoup a sizeable portion of the latent heat of the water vapor. Steam is supplied to the first-effect evaporator, causing the salt water therein to be partially vaporized. The heated vapor from the first effect is allowed to pass through a second effect, where it condenses and heats more sea water, the vapor from which passes to a third effect, where it condenses and heats more sea water whose vapor passes to a final condenser from which much of the remaining heat is transmitted to the inflowing raw sea water. Units of this type having as many as six effects have been built in attempts to gain high thermal efficiencies. All parts of the equipment contacted by sea water must be made of corrosion-resistant materials.

**Vapor-compression Evaporators**

The vapor-compression evaporators are a more recent development
Triple-effect evaporation

Vapor-compression distillation

Adapted from an illustration in "Power" by permission

Fig. 2a—Distillation systems
Fig. 2b—Distillation systems
and operate on the heat-pump principle. Vapor is withdrawn from an evaporator shell by a pump. It is then compressed to increase its condensation temperature a few degrees and returned to a heat exchanger within the evaporator shell, where its latent heat is given up to produce fresh water and evaporate more saline water. The energy economy of this system is better than that for multiple-effect evaporators and it can be built more compactly. Although only relatively small units of this type have been built and operated so far, there are no engineering reasons why large units could not be constructed. There are also indications that improvements in heat exchangers, pump efficiencies, and scale control may allow up to a doubling of the efficiencies of this type of evaporator in the future.

Temperature-difference Evaporators

In 1930, Claude proposed using the rather large temperature differences which occur between surface and deep ocean waters in certain parts of the world to produce both electric power and potable water. An attempt to construct a plant in Cuba failed when great difficulty was experienced with the deep water pipeline. Temperature differences of a similar magnitude also occur between inlet and outlet cooling-water temperatures in steam or diesel electric plants and industrial processing plants.

Scientists at the University of California are re-exploring the application of Claude's original idea. In their system the warm sea water is piped into an evaporator under reduced pressure. A small fraction of the water evaporates gaining its latent heat through a 5°F cooling of the remainder of the water. The vapor formed passes through a turbine (which turns a generator) and then into a condenser which is at a lower pressure than the original evaporator. The vapor is condensed by the cooler sea water. A very small model currently in use requires 10 hp to generate 4.6 hp plus water. However, improvements in efficiency should result if the unit's size is increased. It is estimated that a unit producing 100,000 gal of water per day would produce a little more power than that required to operate the various pumps. (NOTE: The simplified
A SURVEY OF WATER SUPPLY

diagram of this system shown in Fig. 2a is a sketch of a small unit; therefore the numbers shown do not reflect potential values.

Solar-energy Evaporators

The direct use of solar energy to evaporate sea water was employed in one form of the life-raft water kits developed during World War II. The only large solar distillation land unit was operated for about 10 years in the 1880's to furnish water for mule trains hauling minerals in the mountains of Chile. This unit covered a ground area of about 1 acre and produced a maximum of 6000 gal of water per day. A solar evaporation plant has recently been proposed to provide additional potable water for the Virgin Islands. This design is similar in many respects to the Chilean installation. The equipment consists of glass-covered wooden trays to hold the brine and a system of pipes and troughs to collect the fresh water condensate after it has formed on the inside of the sloping glass covers. The solar energy passes through the glass, heats the bottom of the tray, and is re-emitted in the infrared range to be trapped in the still, thereby evaporating water which condenses on the glass.

Certain modifications in evaporation techniques have been proposed which might be applied to several of the systems mentioned. One of these modifications is flash evaporation. Saline water at a given pressure and temperature is released into a chamber at lower pressure; the liquid flashes into vapor and is subsequently condensed. This technique is claimed to reduce the shut-down times required for descaling. Another proposal involves the use of supercritical steam. Improved heat transfer and higher thermal efficiencies are claimed for this practice.

SYSTEMS OTHER THAN DISTILLATION FOR REMOVING WATER FROM SALT

Several methods other than evaporation are proposed for removing the water from the salt. Most of these have not advanced beyond the discussion stage, so they are more difficult to evaluate.
Fractional Freezing Method

Some preliminary studies were made of fractional freezing methods designed to separate fresh ice water crystals from saline water. It is pointed out that the latent heat of fusion of water is only one-seventh that of the latent heat of vaporization. However, in a process where this heat is recovered, the difference is of no theoretical importance. Where freezing temperatures are involved, effective heat transfer to maintain thermal efficiency will be more difficult and more costly. Also, the frozen ice crystals entrap saline water on freezing and make separation difficult. Some German investigators have proposed centrifuging to obtain good separation of fresh ice and brine.

Osmotic Methods

Several variants of systems involving osmotic phenomena have been suggested. When fresh water and saline water are separated in a cell by a semipermeable membrane, the fresh water will diffuse into the saline side and increase the pressure there until equilibrium is reached. This pressure is known as the osmotic pressure of the particular type and concentration of solute. It is possible on small-scale laboratory equipment to reverse the flow of water from the saline side to the fresh side of the membrane by imposing a greater pressure on the saline side than the equilibrium osmotic pressure. However, because of the difficulties involved in measuring osmotic pressures directly by membrane techniques, values for the osmotic pressures of solutions are often determined indirectly by measuring vapor pressures or freezing points. From the point of view of energy requirements, there is no advantage to be gained by imposing a membrane barrier. The same energy would be required per unit of water obtained as in a perfectly efficient thermal evaporation process. In addition, a process of the latter type, such as vapor compression distillation, avoids the tremendous practical difficulties caused by the plugging and failure of membranes.

There are some indications of work being done on a process which utilizes molecular oil films as "membranes" in a pressure osmotic method as described above. No details of the system are available at this time. If by some trick it is possible to maintain liquid "membranes,"
they may eliminate the plugging and failure of film-type membranes.

On a theoretical basis, there should be no difference in the energy requirements per unit of water produced between a liquid membrane osmotic system and a perfectly efficient thermal system. In practice, however, the latter process requires the circulation of a very large portion of the energy (the latent heat of vaporization), so even a small percentage loss of this circulating energy represents a relatively large portion of the energy required for conversion. An osmotic process would not involve the latent heat of vaporization of water; consequently, practical efficiencies might be higher if an osmotic process without membrane troubles could be discovered.

**SYSTEMS WHICH REMOVE SALTS FROM WATER**

Processes which remove salts from water have one basic advantage over systems that remove the water from salt water — their costs will usually vary significantly with the amount of dissolved solids present and the amount removed. Processes for removing salts are generally chemical in nature. The classic process, of course, is the silver-salt precipitation unit developed for life-raft use during the war. This and other chemical precipitation processes are suitable for emergency use only because of the very high cost of the chemical reactants. Two of the chemical processes of more practical significance are shown in Fig. 3.

**Ion-exchange System**

In recent years cation and anion exchange resins have been developed to a high degree of selectivity. It is possible to pass saline water through a bed of cation exchanger where the cations of the salts are replaced by hydrogen ions from the resin. The resulting dilute acid solutions are then passed through a bed of anion exchange resin where the anions are taken up by the resin in exchange for hydroxyl ions. This can result in a complete desalting of the saline water to yield a distilled water equivalent. The resins, however, have only a certain capacity for exchange before they must be regenerated — the cation exchanger with an acid, and the anion exchanger with a base. In addition to the costs
FRESH WATER FROM THE SEA

Ion exchange

Electrolytic-ion exchange

Adapted from an illustration in the "Journal of the AWWA" by permission

Fig. 3—Chemical systems
for these acids and bases, some of the desalted water must be used in the regeneration cycle. These factors limit the competitive position of this system to treatment of brackish waters of 2000 ppm or less. An ion-exchange process pilot plant has been installed in Israel to study the removal of about 1000 ppm of salts from brackish waters. This degree of desalting may make these waters potable and suitable for irrigation.

Electrolytic Ion Exchange

Ion-exchange resins — incorporated in an inert resin and rolled or extruded into sheets — form the basis of new desalting processes which, perhaps too strongly, have raised hopes for a cheap fresh water manufacturing system. Although no technical details have been released, it is possible to reconstruct the working of the process from prior technical papers and the very general description of the equipment released so far.

Imagine an insulated tank filled with saline water and containing an inert electrode at each end. If direct current is caused to flow through the salt solution, electrolysis will take place. The reaction at the cathode can be represented as

\[ 2e^- + 2H_2O \rightarrow H_2 \uparrow + 2OH^- \]

The reaction at the anode will be

\[ 2H_2O \rightarrow O_2 \uparrow + 4H^+ + 4e^- \]

Within the solution the current is carried by the motion of the dissolved ions — the negative ions moving toward the anode, the positive ions toward the cathode. Under these conditions, of course, water is used up to form hydrogen and oxygen gas and the solution becomes more concentrated. However, if two membranes are placed across the cell dividing it into three sections, and if one of the membranes is cation permeable and the other anion permeable, fresh water will eventually be formed by the electromigration of the ions out of the center portion. The cations will flow to the cathode through the cation permeable membrane (the excess OH\(^-\) there cannot flow back through this membrane
— it is anion impenetrable), and the anions will flow to the anode through the anion permeable membrane (the excess H⁺ there cannot flow back through this membrane — it is cation impenetrable).

A simple two-membrane three-cell system would be very inefficient because each coulomb of electrical energy would decompose one mole equivalent of water and transport only one mole equivalent of salt. However, if many sets of membranes forming many cells (alternate salt and fresh) are placed in the tank, each mole of water electrolyzed will cause the transport of one mole equivalent of salt in each of the cells in the tank. Thus, the current efficiency theoretically increases directly as the number of cells is increased. In practice, the current efficiency is probably largely controlled by the amount of internal electrical resistance of a bank of cells, especially the resistance of the alternate cells containing fresh water. An actual operating unit would probably be constructed to allow a continuous flow of the salt water and de-ionized water through the alternate cells, which would be made as thin as possible to reduce resistance.

Claims for electrical energy requirements as low as 20 to 30 kw-hr per 1000 gal of water reclaimed from sea water and total costs of 10 to 20 cents per 1000 gal ($32.50 to $65.00 per acre-foot) of fresh water produced were originally made for this process. No details of the way these costs were derived could be obtained, but they are believed to be extremely optimistic. Just recently, news items have reported estimated costs of $500 per acre-foot for this process.

The costs of fresh water produced by this system should vary with the amount of dissolved salts to be removed from the water. First applications of the method, therefore, will probably be for the demineralization of brackish water, where it may have cost advantages over the bed-type regenerative ion-exchange process.

**Estimated Costs of Manufacturing Fresh Water from Saline**

The costs of producing fresh water by the different systems described are much harder to estimate than their technical feasibility. Only a few
plants of capacity large enough to supply water to a community have ever been built. Some of the processes suggested have not even been operated on a laboratory scale. In addition, many of the costs quoted in the literature are suspect because no details are given as to whether amortization, obsolescence, operating expenses, and energy costs have all been taken into account. A few of the processes appear to have about reached the peak performance allowed by the present or estimated future states of the art. In other instances considerable advancement can be anticipated with improved technology. No attempt will be made in this brief survey to derive detailed cost estimates for each of the processes. However, estimates which appear to be the most reliable have been taken from the literature and are presented in Table 3. Costs will of course vary with the scale of the operation, but in almost every case the range of uncertainty is so great as not to warrant expressing cost as a function of output. The scale envisaged is, however, that appropriate for community supply rather than laboratory tests.

The first cost figure in the table represents estimates based on the present state of the art in each category. The second figure is an extrapolation based on possible improvements of the state of the art in the future. The estimated plant costs are written off in 15 years. Plant costs for natural water sources (dams, aqueducts) are usually written off over longer periods—even up to 50 years. But a good case can be made that these two periods are representative of the useful lives expected from the types of plants involved.

The costs given previously for natural water in California, ranging from $5 to $100 an acre-foot, are representative of water costs in many parts of the United States and are from 2/3 to 4/3 of the estimated present costs for synthetically produced water. Ultimately, in those areas where the next increment of natural fresh water appears to cost more than the same increment of water produced from the sea by an improved conversion process, the latter should, of course, be given serious consideration.

There are areas in the world where natural water costs already approach the cost of water produced from the sea by known processes and where demand for additional water might be generated by domestic


Table 3
ESTIMATED PRESENT AND FUTURE LARGE-SCALE
COSTS FOR SELECTED SALT-WATER
CONVERSION PROCESSES

<table>
<thead>
<tr>
<th>Type of Process</th>
<th>Estimates of Costs ($ per acre-foot of fresh water produced from sea water)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Present</td>
</tr>
<tr>
<td>Multiple-effect evaporation</td>
<td>1200²</td>
</tr>
<tr>
<td>Vapor compression</td>
<td>700³</td>
</tr>
<tr>
<td>Temperature difference (Claude)</td>
<td>150⁴</td>
</tr>
<tr>
<td>Solar evaporation</td>
<td>350⁵</td>
</tr>
<tr>
<td>Freezing</td>
<td></td>
</tr>
<tr>
<td>Ion exchange</td>
<td></td>
</tr>
<tr>
<td>Electrolytic ion exchange</td>
<td>500⁶</td>
</tr>
</tbody>
</table>

²From estimates made by T. K. Sherwood, Dean of Engineering, Massachusetts Institute of Technology.
³For multiple effect, evaporator operated on waste heat. Sherwood's figures reduced by Aultman's estimates of fuel costs.
⁴From estimates of future possibilities made by Allen Latham, Jr., Arthur D. Little, Inc.
⁵From French estimates of the cost of building a plant in Abidjan, French West Africa; increased by $1,000,000 to cover costs of undersea pipeline.
⁶Plant using waste heat, no undersea pipelines; again using French estimates.
⁷From estimates of Maria Telkes, Massachusetts Institute of Technology, and E. D. Howe, University of California.
⁸"In the blue" estimate made by supposing a more ideal process with over-all efficiency of 20 per cent. and evaporators, pumps, etc., costing $6.00 per sq ft of surface; maintenance and operating expenses $0.30 per 1000 gal.
⁹Estimate by Aultman.
¹⁰Estimate quoted by manufacturer to Congressional subcommittee.
¹¹"In the blue" estimate made on same plant costs at (g), above, increased by 30 kw-hr per 1000 gal direct-current requirement.
needs or by desire abroad for the commodities exported by the region (e.g., petroleum products along the Persian Gulf). It is reasonable to expect that production of fresh water from the sea will be first applied in such areas, rather than in the United States.

As among conversion processes, those which use temperature differences such as occur in the sea and those which use direct solar radiation appear the most promising. It should be mentioned that until the cost of power generated by nuclear reactions can approach the cost of power produced by conventional means, there is no reason to consider nuclear power as a panacea for the cheap production of fresh water from the sea. There may be areas in the world where for critical reasons it is essential to have a supply of potable water and electric power (an isolated military base, for example). If it proves cheaper to generate the power by nuclear reaction rather than to transport conventional fuels to the area, then some of the power, including waste heat, can also be used to produce potable water from the sea.

It will be recalled that the cost per unit of water for processes which remove salt from the water is much lower when only small amounts of dissolved solids are removed. These processes may be applied soon to the treatment of brackish waters where removal of one or two thousand parts per million may produce water suitable for irrigation. The counterflow ion-exchange system may remove one thousand parts of solids for about $190 per acre-foot. One estimate indicates that the electrolytic ion-exchange system might do this job at $10 an acre-foot. However, another and perhaps more realistic estimate places the cost of this process at $110 an acre-foot to reduce the salt concentration from 1000 ppm to 300 ppm.

Throughout this analysis, no cost reduction has been credited to the possibility of producing salable by-products. It is technically feasible to extract many potentially valuable products from sea water—at least traces of perhaps half the elements are actually present. Apparently, however, only sodium and magnesium salts and bromine are presently at all economic to extract. The increased concentration of the waste brine flowing from a desalting process may confer a certain cost advantage over present salt extraction plants which must begin with
ordinary sea water. However, it is our impression that no substantial profits are attainable by presently known techniques, mostly because the value of the easily extracted salts is so low. A rigorous proof of this point requires an examination of each product which might be produced from sea water in respect to its present supply and the demand at possibly reduced price levels. Different techniques for producing each product must also be studied to determine their compatibility with the sea water conversion processes of interest and the potential cost of the by-products inherent in the process. Such a study is beyond the scope of this brief survey. However, our impression of the possible value of by-products in reducing conversion costs, as stated above, is reinforced by a detailed study made recently by the Conservation Foundation.
METHODS OTHER THAN SALINE WATER CONVERSION FOR INCREASING SUPPLIES OF WATER

The production of fresh water from the ocean seems to appeal to the popular imagination more than its present or future capabilities, at least in our country, warrant. Other ways for increasing or expanding the natural water supply deserve more emphasis than they have received. These possibilities fall generally into two main categories — those which conserve present water resources in an area, and those which increase the equivalent natural supply of water. These possibilities will be discussed briefly in the following sections.

Conserving Supplies of Natural Water

RECLAIMED WATER

Proposals for reclaiming usable water from sewage have been mentioned previously. This practice is already unintentionally used in many parts of the United States and Europe. There have been a few intentional applications of the process. Almost every river or stream flowing through urban areas of the eastern United States permits the inadvertent reuse of water from sewage. Treated or untreated sewage is dumped into a river by a city upstream and, diluted and reacted upon by the flowing water, is pumped into the water system of a city downstream. Another inadvertent use occurs in Southern California where the outflow from thousands of septic tanks in the Coastal Basin enters the underground aquifers to be subsequently repumped for municipal and irrigation purposes. When properly controlled, this cycle does not seem to represent a health hazard. The movement of water from sewage through about 6 ft of soil appears to reduce the presence of most harmful enteric organisms below a tolerable level. There are questions
which remain to be answered, however, if the intentional reuse of water from treated sewage is to be applied on a large scale. Very little is known about the length of time recharging areas remain effective when large quantities of reclaimed water are percolated through them to the aquifer. Also, more must be learned about the degree of treatment required for each of the ultimate uses for the water. It is necessary to avoid building up certain mineral components in the aquifers. For example, the nitrate content must be held below a certain maximum level to avoid a possible pathological condition in young infants. Boron, from sewage waste containing borax (used in packing houses), is harmful to many crops. Certain legal problems must be overcome to provide for the formation of Reclamation Districts. However, when all factors are considered, it appears that reclaimed water from sewage could be made available at a lower cost than fresh water from any sea water conversion process. In Southern California more water from sewage is available than is now brought in from the Owens-Mono watershed. As more Colorado water is used in the area (as a result of population increase), even more water for reclaiming will be available.

EVAPORATIVE LOSSES

Evaporative losses from storage lakes, reservoirs, and distribution canals are a potential source of water which under certain circumstances may equal the amount of water now being produced from the system. It may be surprising to learn that it is not possible to calculate the actual evaporative losses from a body of water. Until recently it was not even possible to measure the evaporative loss with any degree of precision. Recently a combined effort of the Departments of the Navy, Interior, and Commerce resulted in a fairly precise measurement of the evaporative losses from Lake Hefner in Oklahoma. This reservoir was chosen for study because it is relatively symmetrical in shape, has an almost impervious bottom, and allows easy measurement of input and output. Evaporative loss was determined by difference. Of course the loss rates varied with air velocity, relative humidity, air and water temperatures.
and surface roughness, but it averaged about 90 per cent of the outflow of the reservoir.

With the experience gained at Lake Hefner, the investigators moved to Lake Mead and are presently measuring evaporative loss there. Previously, a guess was made that evaporative loss from the Colorado River Lower Basin main stream reservoir system is of the order of 800,000 acre-feet per year. (The Lower Basin starts at Lee Ferry, just south of where the river crosses the Utah-Arizona line.) However, if evaporative loss from Lake Mead even approaches that found at Lake Hefner, the actual evaporative loss for the Lower Basin may be considerably greater than the value above.

Since excess water is presently available from the Colorado, there is little incentive to study means for reducing evaporative loss. However, there are areas in the world where the water gained by reducing evaporation may well prove to be the cheapest source of additional supply. Moreover, as demands increase in the southwestern United States, it may prove cheaper to gain water from the Colorado by reducing evaporative loss than to bring the additional amount required from the more distant watersheds.

No methods of reducing evaporative loss were found in the literature. It can be postulated that losses increase with the surface area of water exposed; with high radiant energy absorption by the water; with higher air and water temperature; with higher air velocity and water surface roughness; and with lower relative humidity. This suggests that methods which favorably change any of these parameters will reduce evaporative losses. Such measures as oil layers or flexible buoyant insulating covers floated on reservoirs may be cheap and yet effective in markedly reducing evaporative loss. They might, however, interfere with other uses of water, such as recreational use.

**EVAPOTRANSPIRATION LOSSES**

The problem of evapotranspiration loss of water is receiving more attention. For the United States as a whole it is estimated that 72 per cent of the average precipitation is returned to the atmosphere by evapo-
transpiration.* Some of this loss occurs in the growth of plants beneficial
to man (crops, forests). However, an unknown amount is consumed
by undesirable vegetation. Plants such as salt pine grow in profusion
along watercourses in otherwise sparsely vegetated regions. These and
similar plants are greedy consumers of water. They send roots deep
into aquifers along watercourses and essentially waste large quantities
of water. In some areas large quantities of this undesirable growth are
being removed to the advantage of beneficial plant growth. Costs of
water recovered in this manner cannot be estimated as yet. The whole
subject of evapotranspiration relationships in arid regions requires
more study.

The “popular” concept of the relationship of native vegetation to
water supply, especially in the mountainous portions of drainage basins,
is largely erroneous. The native, perennial vegetation of the arid and
semi-arid areas has adjusted itself to the mean precipitation of the areas.
The plants are deep-rooted and draw their water from a large volume
of the soil. The common belief is that if the brush is removed from the
watershed, the drainage basin water supply will be reduced because of
soil erosion and rapid runoff. Actually, when accompanied by the
proper soil conservation practices, the removal of nonbeneficial plants
can result in a net increase in water supply through reduced evapo-
transpiration loss.

ECONOMIC MEASURES FOR CONSERVING WATER

Several economic measures may assist in extending water supplies.
Again, the Southern California Coastal Basin is used as an example,
although the measures suggested should find universal application.

The dark spot in the generally favorable local water picture — and
possibly the major cause of all the talk about a Southern California
water shortage — is the ground water situation. The water levels in
the aquifers underlying the South Coastal Basin have been dropping
steadily because of pumping overdraft. The result has been an increase
in the cost of water from underground sources and an intrusion of sea

*It will be recalled that evapotranspiration is that process whereby water from the
ground passes through the life process of a plant and from the leaves to the atmosphere.
water into the aquifers for a distance of two to three miles inland from
the coast in some areas. The important thing about these costs is the
different way in which they are borne: the increased cost of pumping
falls upon all users of underground sources, but the intrusion of sea
water involves a major loss to those directly affected and no loss at all
to those in inland areas who may be equally responsible for the
condition.

The comparative cost situation is approximately as follows: Pumping
costs at present are around $5.00 per acre-foot, while the Metropolitan
Water District supplies aqueduct water at a wholesale price of $10.00
unsoftened, $20.00 softened. The retail price of water to consumers is,
furthermore, higher than the wholesale price set by the Metropolitan
Water District. The "shortage" then is one of $5.00 water, since the
higher-priced alternatives are readily available. Of course, the alterna-
tives faced by the man who sees his pumping costs slowly rise from
$5.00 to $6.00 or $7.00 are very different from the alternatives faced
by those property owners whose ground waters have been ruined by salt
water intrusion.

If it were not for the latter problem, there would be no particular
need to do anything about the situation. Eventually, omitting the in-
trusion problem, an economic equilibrium would be reached. This would,
of course, be lower in general from the "natural" equilibrium in which
the water level, in the absence of pumping draft, would rise until inflow
became balanced by runoff to streams and ocean. At this economic
equilibrium, the cost of pumping would have risen so high that many
marginal users would have been forced out or forced at least to reduce
their drafts upon the system. Then, the water inflow would eventually
balance drafts. Economic equilibrium would also tend to be brought
about by a shift to less water-intensive uses of the land, or a shift to a
source of water other than the underground aquifer.

The sea water problem changes this picture because, first, sea water
intrusion may do such irrevocable damage to the aquifer that it might
seem worth while to sacrifice present use of the water to preserve its
future potentialities. However, despite conservationist dogmas, it is
sometimes advisable to sacrifice future potentialities for present needs.
For example, strict adherence to such dogmas would require abandonment of practically all mining operations. There is no necessary reason for it to be always inadvisable to "mine" our water resources, though in this particular case we might decide to preserve the future potentialities. Secondly, the losses due to overpumping are borne disproportionately, and therefore, perhaps inequitably, by property owners near the sea coast. In consequence, the private cost of pumping does not fully reflect the social cost — which should take into consideration the losses suffered by those whose ground waters are contaminated.

Even in the absence of sea water contamination, the private cost does not fully reflect the social cost, since any individual's pumping operations draw down the aquifer at the cost of the whole community of pumpers and potential pumpers. Thus, even if I do not pump this year, I still must bear, in increased pumping costs for the future, part of the costs of everyone else's drafts upon the aquifer. These losses, however, are more gradual and so less conspicuous than the losses of those who suddenly lose their ground water sources entirely.

The general economic solution for a divergence between social cost and private cost is a tax or a subsidy. In this case a water-use tax upon pumpers is needed to reflect the social cost to the community of the drawing down of the water table in general, and the consequent intrusion of sea water in particular. Another possible solution is to prorate the water to be drawn, a more obvious but comparatively crude and inefficient line of attack. The prorating system is necessarily arbitrary (rationing by historical use or by direct assessment is so objectionable that it is difficult to choose between the two), and in addition has the wrong effect on incentives. Instead of a general encouragement to economize water, prorating offers no bar at all to waste of water until one's allotment is reached, and thereafter permits no use whatsoever, however intense or well-justified the need. A simple tax per drawn unit provides a consistent and general discouragement to wasteful use, is as easy to enforce as prorating, and provides some revenue which can be used to repair the social losses resulting from the overdraft of water. Ideally speaking, the tax should be just heavy enough so that the revenue would cover the losses which could be ascribed to the fall of
the water table. In practice, we would be satisfied with a very rough approximation of this ideal.

Another promising possibility, complementary to the water-use tax, would be consumptive pricing of water. Consumptive pricing would charge more for water which is "used up" (water which is lost in evaporation, in runoff, or "spoiled" by contamination) than for water which is returned to the aquifer ready for reuse. The simplest form in which to connect consumptive pricing to ground water use would be as a rebate on the tax paid, the rebate to vary with the degree of "spoilage" of the water and the amount returned. Water could re-enter the aquifer by ground soaking or by recharging through wells, and an appropriate credit could be granted for each.

This measure would encourage industry to adopt nonconsumptive use techniques in their production processes. It is known that the consumptive use of water can vary widely among a group of factories producing the same product. By using intelligent conservation practices, a large industrial plant can actually be a net contributor to the aquifer from which it draws its water, as at the huge Geneva Steel plant near Provo, Utah. This plant draws 240 million gal per day, but only uses about 3 per cent of this consumptively. This small use is more than made up by the decreased evapotranspiration loss in the plant area.

Assisting Nature To Increase Present Natural Water Supplies

Since prehistoric time man has attempted to make rain. The Indian medicine man and the French cannoneer had their loyal adherents, but their efforts were of very dubious value in producing rain as ordered. Since the last war we have learned a little more about what conditions are conducive to cloud formation and precipitation, but our general knowledge of the subject is still limited. The process of artificially nucleating clouds to produce precipitation is being widely used today with uncertain over-all results.

It is known that under natural atmospheric conditions water vapor may exist in clouds in a metastable supersaturated condition with respect
to ice, and that water droplets may be supercooled with respect to ice. It is also known that foreign particles having certain hygroscopic and structural characteristics can initiate and speed up the formation and growth of both water droplets and ice particles under the right conditions of temperature and saturation. For effective nuclei, this action has the result of materially reducing the degree of supercooling which exists within a cloud. The General Electric Company conducted laboratory experiments to determine the relative nucleating effectiveness of many types of particles, rating them on the reduction in supercooling they produce. Everyone is familiar with attempts to use nucleation to produce increased rainfall. Artificial nucleation is actually being carried out on a contract basis by commercial "rain-making" organizations. The effectiveness of such operations, however, remains in doubt.

It is beyond the scope of this survey to explore all of the legal, social, economic, technical, or metaphysical arguments which have been advanced to support or disprove the value of artificial nucleation for increasing precipitation. However, a review of the literature and discussions with meteorologists indicate the following conclusions about nucleating efforts to date:

1. There is some evidence, still not universally accepted, which suggests that artificial nucleation may slightly modify the precipitation pattern over a wide area downwind. Although this effect may represent a perturbation of the normal, it does not appear to be significant in changing the climate.

2. The primary effects of nucleation are in a localized region and last for a short time, so that precipitation may be encouraged to occur a little sooner than it would otherwise in a situation where rain is likely to occur naturally.

3. It is difficult to evaluate the degree of any localized increase in precipitation through nucleation because past rainfall figures have not been collected at a sufficient number of stations to determine past natural fluctuations within a local region.

4. There are a few local areas where sharp terrain features combined with the short-range effects of nucleation have produced a significant increase in local precipitation.
5. The details of the processes of precipitation are still poorly understood, but there is evidence that artificial nucleation under some conditions serves to decrease rather than increase precipitation.

It appears that, while nucleation may have beneficial effects in increasing precipitation in certain specific local areas, it is not a general panacea for increasing precipitation and available water supplies.

The lack of adequate knowledge about the operation of the hydrologic cycle has been mentioned several times in this report. The comment is especially pertinent to that part of the cycle in which water is evaporated from the oceans and precipitated upon the land. In particular, more information is needed about the physics and thermodynamics of cloud formation. Better knowledge is required of the internal mechanisms of cloud and precipitation formation and the relationships of clouds to their environment — the land surface beneath, the surrounding dynamic atmosphere, and the atmosphere above. Mr. Lewis W. Douglas, former Ambassador to England, has made a worthy effort in this direction by promoting an institute for the basic study of cloud physics. The Conservation Foundation in New York has been sponsoring and directing some extremely valuable studies of the ground aspects of the hydrologic cycle. Man’s potential ability to exercise some control over weather, including precipitation, depends on a more complete understanding of the natural processes involved. What has been accomplished so far, including the practical application of synthetic nucleation of clouds, is but a first step in this direction.

Although it is presumptive to speculate at this time on the techniques such control of weather may employ, some general trends may be observed:

1. Efforts to alter climate by attempting to feed in or remove energy will probably not be profitable except in a very small area. The total energy contained, even in small volumes of the atmosphere, is huge in absolute magnitude.

2. Any successful attempts to alter climatic conditions will probably employ a combination of techniques which “trigger” or
encourage the weather desired by working through and with natural forces. Several examples will help to clarify this point.

A reference has been made to the success of a combination of synthetic cloud nucleation and favorable terrain features in inducing precipitation. Hills and mountain ranges trigger precipitation under certain conditions through their aerodynamic effects on the atmosphere. Perhaps the use of artificial, portable, aerodynamic barriers combined with nucleation might produce important results.

The albedo of a surface is the percentage of incident solar energy received by the surface which is reflected. For the earth's surface, this varies from 3 per cent for green fields or forests to 86 per cent for fresh snow. A desert reflects about 26 per cent of the energy. The stability of clouds is influenced (among other factors) by the amount of energy received from the earth's surface. Thus, if the albedo or the infrared emission of large areas can be reduced, more clouds may form above these surfaces, permitting opportunity for precipitation. Alternatively, if the temperature distribution of the surface could be formed into regular patterns, it might be possible to induce convective activity over the heated sections, thereby causing cumulus-type clouds and rain. The radiative balance of a desert might be changed artificially by (1) plowing, (2) spreading a layer of black material, (3) inducing the growth of black molds or other vegetation requiring little water. These measures plus artificial barriers plus nucleation (if necessary) might induce nature to increase the amount of precipitation in desert areas. Another device which might be useful for favorably altering the relationships of clouds to their environment is the application of artificial thermal barriers (e.g., releasing water vapor in patterns underneath and above the clouds).

The specific suggestions made here are, of course, merely research possibilities, since little is known as yet regarding their practicability.

The Direct Use of Sea Water

For many purposes the direct use of saline water is almost as satisfactory as fresh water. Bathing, washing, sanitary uses, and fire protec-
tion could be satisfied by water too saline for human consumption. Many industrial purposes also could be served by saline water. However, since some fresh water will always be required for residential and industrial use, an expensive dual piping and plumbing system for municipal areas would be required. In arid and semi-arid regions, agricultural irrigation presents the greatest demand for cheap fresh water. Saline water cannot be used in present agricultural practices.

More attention might, perhaps, be given to the possibilities for increasing the supply of food for arid regions near the sea (or near saline water equivalent to sea water) by the effective development of what is known as ocean farming. The artificial culture of oysters for pearls and food represents the most advanced development along these lines.

By proper fertilization, farmers can grow today more meat (fish) in a fresh-water acre pond than they could produce (in pork or beef) if the same acre were devoted to feed crop. The ocean-fishing industry, on the other hand, still produces by a method similar to that used by the Indians to provide meat for themselves — i.e., by hunting. Admittedly, advanced techniques, such as locating schools of fish by radar and self-contained fish-packing ships, are now in use to great advantage. However, the technical and economic possibilities for raising food fish synthetically in closed ocean areas near to the points of consumption have perhaps not been fully explored.

The same applies to vegetative crops grown purposefully in "farmed" ocean areas. The varieties of plant life occurring in the oceans are much fewer and generally simpler than those which grow on land. However, they provide the basic food for all the extensive marine animal life. Some marine plants might be artificially cultivated for use as animal or human food. Or even better, land forms of vegetation — perhaps rice — might be adapted to marine growth by a process of selective breeding. Some of the highest forms of marine plants appear to have been land forms that have become self-adapted to marine growth.

Further study of ways such as those mentioned in which nature may be encouraged to increase the effective amount of fresh water available to man, either through increased precipitation or direct use of the sea,
may show many or all to be technically impossible or economically unsound. These possibilities are presented to indicate that there may be more favorable alternatives than the conversion of sea water to fresh water to meet man’s increasing future demands for water.
CONCLUSIONS

The major conclusions of this brief survey are summarized as follows:

1. The review of possible methods for producing fresh water from sea water indicates that with the present states of the art, estimated costs will range from $150 to $1200 per acre-foot (325,851 gal) for the conversion, depending on the process used. Presently, natural fresh water in the United States ranges in cost between $1.50 and $50 an acre-foot. Postulated future improvements in various processes may permit fresh water production from the sea at costs ranging from $100 to $900 per acre-foot.

2. Until the costs of transporting fresh water from the areas of oversupply to the areas of greatest demand equal or exceed the costs of making fresh water from the sea locally, there is no incentive to construct sea water conversion plants. Along the west coast of the United States (where the water situation was examined in greatest detail) natural water appears to be cheaper than the lowest cost sea water conversion processes for meeting foreseeable demands for decades in the future, assuming no radical increase in the rate of population growth.

3. The supply of very cheap local water ($1.50 to $6 an acre-foot) for agricultural purposes is about used to the limit in many areas of the western United States. Some extension in the supply of this water might be obtained by conservation measures such as synthetic recharging of aquifers by excess runoff water and reduction of evapotranspiration by nonbeneficial plant growth; but, in general, agriculture in these areas will have to readjust to higher water costs for the next increment in crop production.

4. The use of water reclaimed from sewage and the reduction of evaporative losses from present reservoir systems promises an increased water supply for heavily populated areas which may be cheaper than
the cost of the next increment of water transported into the area from a greater distance.

5. More rational, less wasteful use of existing water supplies may be attained by improvement of the pricing system: in particular, by charging for consumptive rather than gross use, and by water-use taxes where the private cost of producing water, as in pumping from a common aquifer, is less than the social cost.

6. Installations for the production of fresh water from the sea will find their first applications in those isolated parts of the world where potable water is required for human habitation but where the costs for transporting and storing natural fresh water exceed the cost of water made synthetically. One or more of the processes which remove salt from water (as against water from salt) may find more extensive use in treating brackish waters to remove one or two thousand parts per million of dissolved solids and thereby provide water suitable for animal and plant consumption.

7. A better understanding of the hydrologic cycle through research may point the way to practical ways for controlling precipitation. The possibilities for the direct use of the oceans for the controlled production of food also merit exploration. Either one or a combination of these practices may conceivably have much greater implications for the well-being of larger world populations than any of the processes which are presently conceived for production of fresh water from the sea.
BIBLIOGRAPHY

Acknowledgment

The expert and friendly assistance of M. R. Anderson and N. Nimitz in preparing the following bibliography is gratefully acknowledged.

A. GENERAL OR SUMMARY MATERIAL


"California's Stake in the Colorado River," Colorado River Board of California, March, 1951.

Compendium of Meteorology, American Meteorological Society, 1951.


Discusses testimony before Senate Committee considering legislation to promote sea water research. Testimony seems to favor vapor compression as most efficient distillation unit.
A SURVEY OF WATER SUPPLY

"History and First Annual Report," The Metropolitan Water District of Southern California, 1939.


Surveys the various methods of desalting salt water besides the distillation methods preferred by engineers.

Surveys attempts from 16th to 20th centuries to convert sea water to potable water, and describes typical modern low-pressure (steam) evaporators and vapor compression plants. Brief bibliography of early literature.

Objectionable characteristics of saline water are stated. For desalting, evaporation and ion-exchange are the only methods economically feasible. Thermal, vapor, and solar evaporation are discussed in comparison with complete removal by ion exchange. In the latter the effect of quantity and quality of impurities is studied. Above 2500 ppm total salts evaporation processes become apparently more effective and economical. (Chem. Abstracts, 1952, p. 3185.)


B. EVAPORATIVE PROCESSES

A vapor-compression distillation unit is described and its operating principles are dis-
cussed. The water produced is of good quality and meets all U.S.P. requirements; pH adjustment is considered advisable if the water is to be distributed or stored, to prevent corrosion.


Describes project to produce both power and fresh water by utilizing the temperature difference between surface and deep waters.


Describes design of solar distillation equipment proposed by Maria Telkes of M.I.T. "Data from this installation have not yet been published, but other data published by Telkes indicate a water yield of almost 1 gpd for each 4 sq ft of absorber surface."

(Howe)


Proposes that attention be given to the possible combination of a sea water refining plant with a power generating plant, in order to decrease costs.


Discusses various methods of distillation (diesel waste-heat method, temperature-difference method, and solar distillation). Schematic diagrams show recommended pilot plant design. Article is based on research program now being conducted by University of California to determine whether any of the methods of refining sea water can be developed to supplement normal supplies of water in California coastal cities. Distillation methods were selected as most promising, since distillation can be combined with power generation more easily than can water refining by freezing, chemical methods, the membrane method, or electrolysis. Solar distillation method seems most promising.


Estimates that the art of compression distillation has advanced about as far as can reasonably be expected short of aggressive pursuit of major development projects. It seems unlikely that costs can be reduced to less than half the present costs.
A SURVEY OF WATER SUPPLY

Describes continued research on Claude’s method.


"Efficiency of the process is about 60 to 70 per cent in the tropics. Further developmental work is needed before large-scale solar sea water distillation will be economically feasible." (Panorama of Science, 1952, p. 340.)


C. CHEMICAL PROCESSES (PRECIPITATION, ELECTROLYSIS, ION EXCHANGE)


Bibliography lists 17 patents.

"Brackish Bargain; Ionics, Inc.,” Chemical Week, Vol. 70, March 8, 1952, p. 36.


Mention by Aultman as method of boiler water treatment which has apparent promise for treatment of industrial and domestic waters.


Describes output and use of ion exchangers in 1946. "... Unless new and efficient techniques are developed, resins will not displace inorganic exchangers because of their lower costs and higher capacities." (Chem. Abstracts, 1949, p. 4404.)
BIBLIOGRAPHY


Ionics, Inc. is the group of scientists who have pioneered in the application of ion-selective membranes in electrochemical desalting of sea water and brines.


Records results of experiments confirming the advantages of the countercurrent technique described by Gustafson, above. Dowex 50 in Na and Ca form was regenerated by HCl and H₂SO₄ solutions. HCl was as efficient as H₂SO₄ for regenerating the Na form, and is more efficient than the H₂SO₄ in regenerating the Ca form, owing to subsequent exhaustion by the CaSO₄ formed.


The author is associated with the Israeli Program.


Reports data on operation of Israeli pilot plant utilizing a modification of the ion-exchange demineralization developed by Palestine Research Associates, Cambridge, Mass., and Weizmann Institute of Science, Rehovot, Israel. To achieve maximum economy of sulfuric acid used for regeneration, the countercurrent technique of partial regeneration of the hydrogen-ion exchangers is used. The cost of demineralization by the method presented is estimated to be $0.60 per 1000 gal treated, with 1000 ppm solids (as NaCl) removed.


Description of Briggs' method.


Bibliography (31 references), flow sheet.
A SURVEY OF WATER SUPPLY


Describes new method of preparing improved membranes from suitably ground ion-exchange resins embedded in plastic matrix by compression.

D. OTHER PHYSICAL OR CHEMICAL PROCESSES


Experimental results are reported for block (I), annular cell (II), and agitation freezing (III) processes. Salt concentration was reduced in all three systems. II and III were greatly superior to I. Economic and equipment considerations make III the most promising system when dilution and centrifuging are included. (Chem. Abstracts, 1951, p. 8169.)

E. CONSERVATION; WATER SUPPLIES AND REQUIREMENTS


F. PERSONAL COMMUNICATIONS

DERBY, RAY L., Principal Sanitary Engineer, Los Angeles Department of Water and Power.

DIEMER, ROBERT B., General Manager and Chief Engineer, The Metropolitan Water District of Southern California.

BIBLIOGRAPHY

MILLER, HOWARD A., Assistant General Manager, Los Angeles Chamber of Commerce.

SNIDER, ROBERT G., Vice-President, The Conservation Foundation, New York, N.Y.