8

Western Water Resources: Means to Augment the Supply

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Introduction

Other speakers in the symposium have been charged with the responsibility for reporting on the dimensions of the water resources problems of the western United States, both as to quality and quantity. In this paper I shall set forth some ideas as to how supplies can be augmented to meet demands in terms of water quality as well as quantity and will go on to discuss policies to cope with the water resources problems that must be faced in the future if the West is to continue to prosper. The water supply-demand background upon which this presentation is based, in the absence of prior knowledge of what the earlier speakers will be presenting, is the recently published first volume of the Second National Assessment of the Nation's Water Resources, 1975–2000, prepared by the U.S. Water Resources Council under the authority of the Water Resources Planning Act of 1965, Public Law 89-80.

The Water **Supply**

For the purposes of its assessment, the Water Resources Council has divided the United States into twenty water resources regions. Ten of these are wholly or partly included within the seventeen contiguous western states that comprise the West, as commonly defined. River basins, of course, are not cognizant of political boundaries, so to be strictly accurate the summarized data for the ten water resources regions should be adjusted by deleting that portion relating to the easternmost portions of the Souris-Red-Rainy, Missouri, Arkansas-White-Red, and Texas Gulf regions. For the purposes of this paper, however, such refinement is not necessary, and for the sake of simplicity, the streamflow and water use figures for the entire basins are used.

The Second National Assessment shows a total mean annual runoff from the ten western water resources regions of 459 billion gallons a day (bgd). In 1975, base year for the assessment, there were substantial overdrafts of ground water resources, primarily in the Arkansas-White-Red, Texas Gulf, and lower Colorado regions that augmented the available supply by about twenty bgd. Such augmentation cannot be sustained for more than another decade or so, because of the rising costs of pumping and the finite capacity of the aquifers.

The Demand

Against this water supply, the Water Resources Council has estimated that 175 bgd were withdrawn in 1975, the base year for the study, and has projected, under a variety of assumptions, that this will increase to 187 bgd by 1985, and then decrease again to 177 bgd by the year 2000 as the cost of water and environmental regulations increase. The "bottom line" in water demand, however, is not withdrawal, but consumptive use: the amount of water that is not returned to the stream or ground water aquifer, but is evaporated, transpired, incorporated into a manufactured product, or polluted to such an extent that it cannot be reused. The Water Resources Council estimates consumptive uses in the ten western water resources regions at 88.7 bgd in 1975, or about 19 percent of the supply, and projects increases to 96.8 bgd by 1985, 21 percent of the supply, and to 100.7 bgd, 22 percent of the supply, by the year 2000.

The Water Resources Council data is summarized in Table 1, which shows that water use in the various water resources regions bears little relationship to the indigenous stream flow. For example, water use in the lower Colorado water resources region in 1975 was almost three times the mean stream flow, the excess use being provided by inflow from the Upper Colorado and

TABLE 1

Streamflow and Estimated Consumptive Uses of Water Western Water Resources Regions (in billion gallons per day)[a]

Water Resources Regions	*Mean Streamflow (runoff)*	*Groundwater Overdraft in* 1975	*Consumptive Uses*					
			1975	*Percent*	*Est.* 1985	*Percent*	*Est.* 2000	*Percent*
Souris-Red-Rainy	6.0		.112	1.9	.204	3.4	.446	7.5
Missouri	44.1	2.6	15.469	35.0	19206	43.5	19.913	45.0
Arkansas-White-Red	62.6	5.5	8.064	12.9	8.769	14.0	8.887	14.2
Texas-Gulf	28.3	5.6	11.259	39.8	10.227	36.3	10.529	37.3
Rio Grande	1.2	.7	4.240	353.0	4.320	360.0	4.016	336.0
Upper Colorado	10.0		2.440	24.4	3.018	30.2	3.232	32.3
Lower Colorado	1.6	2.4	4.595	288.0	4.754	297.0	4.708	294.0
Great Basin	2.6	.6	3.779	145.0	3.765	144.0	4.036	155.0
Pacific Northwest	255.3	.6	11.913	4.7	14.610	5.7	15.196	6.0
California	47.4	2.2	26.641	56.5	27.932	59.0	29.699	62.8
Total, 10 western regions	459.1	20.2	88.714	19.3	96.805	21.0	100.662	22.0

[a] One billion gallons per day = 1,120,000 acre-feet per year.

ground water overdraft in central Arizona. An even greater disparity is shown in the Great Basin, but similar ground water overdrafts and importation into the Arkansas-White-Red water resources region are hidden in the table by the fact that the region includes areas of heavy precipitation in the eastern part of the basin.

Supporting volumes of the Second National Assessment, not yet published, show these variations in more detail by dividing the ten western water resources regions into fifty-four aggregated subareas. Use of this data would permit more accurate consideration to be given to water resources shortfalls and deficiencies in localized areas of the West. The Water Resources Council data are not always consistent with other water supply and use data. More recent studies by Bruce Bishop at Utah State University are more optimistic as to the availability of water in the Colorado River Basin.

Along with the uses summarized in Table 1 (which include uses for agriculture, domestic and commercial purposes, manufacturing, energy production, and the mineral industry), there are substantial instream uses of water, such as for preservation and propagation of fish and wildlife, outdoor recreation, hydroelectric power generation, and navigation. These are difficult to quantify. There is rarely enough water in a stream to satisfy all uses, or else there is too much. Under federal and state laws, use of water for hydroelectric power generation and for navigation in states lying wholly or partly west of the ninety-eighth meridian is subservient to beneficial consumptive uses. Recent court decisions with respect to use of water for fish and wildlife have tended to exacerbate conflicts between federal and state water rights, so the situation is indeterminate. Recreational use of water is not recognized under most state water rights laws, but the importance of recreational use to the economies of the western states is well enough understood that it is generally accepted as an important use of water. Thus, in spite of the fact that the bare statistics may show only about one-fifth of the water in the western water resources regions is actually consumed, there are very real shortages now in several regions, and the likelihood of greater shortages as the West continues to grow is certain. New energy technologies (such as coal gasification and liquefaction and producing oil from abundant oil shale resources of the Upper Colorado Basin) will undoubtedly increase demands for water in the Upper Colorado and the western portions of the Missouri Basin water resources regions.

Associated economic development and continuation of recent population growth will increase demand for water in the Lower Colorado, Great Basin, Rio Grande, and the western portion of the Arkansas-White-Red water resources regions. Some method must be found to meet the demands in order to prevent stagnation of the economy of the West due to lack of water in the twenty-first century.

Alternative Means of Meeting Demands

Demand for water can be satisfied in a variety of ways, including increasing the supply, making better or more efficient use of existing supplies, or by reducing the demand. Among the obvious ways of increasing supplies are creating impoundments or storage reservoirs, either above or under ground, to more completely develop existing water resources, transferring water from areas of surplus to areas of deficient water supply, water harvesting through land and vegetation management, precipitation augmentation, and desalting. Less obvious but potentially possible ways include such practices as better forecasting of hydrologic events, augmenting fog drip, snow and icefield manipulation, iceberg towing, undersea aqueducts, and collapsible bladders for transport of large quantities of fresh water through the ocean. Some of these techniques would obviously be applicable only in coastal areas, but could benefit water-short areas in interior regions through exchange.

When the costs of augmenting water supply through any of the above techniques are considered, the advantages of increasing efficiency of use or otherwise reducing demands become evident. There are numerous ways of doing this, including institutional changes such as revisions in state water rights laws where they impede or deter efficient water use, pricing systems to motivate more efficient water use, integration of ground and surface water, and reuse of water. The following sections of this paper cover these points in more detail.

Additional Impoundments

Construction of dams and storage reservoirs has been the most frequently used method of augmenting water supplies. Capacity of storage reservoirs in the United States has increased from 33 million acre-feet in 1920 to 273 million acre-feet in 1953 and 450 million acre-feet in 1975. About 20 percent of this is in the Colorado River Basin. It should be obvious that full offstream use of the average annual streamflow in any water resources region as shown in Table 1 could not be achieved without sufficient holdover storage in reservoirs to equalize the flow over a long period of years. Even with the tremendous storage capacity in the Missouri River main stem reservoirs, it is not possible to operate the system without some spills during floods, so that full regulation has not been achieved. An even smaller portion of the Columbia River system is regulated by reservoirs, but the immense snowfields and glaciers in the headwaters of the river system in Canada achieve somewhat the same purpose as reservoir storage, holding back winter precipitation for gradual release as they melt during the summer months. Complete control of a major river system in an arid climate cannot be achieved without going past the point of diminishing returns, however, as the increase in evaporation from the surface of the reservoirs as complete control is approached will exceed the increase in yield resulting from the addition of another reservoir. This condition has been reached in the Colorado River Basin, according to an analysis in U.S. Geological Survey Circular 409, and probably in the Rio Grande Basin. Storage in small reservoirs and farm ponds, while tending to equalize flows in small drainage basins, also has an adverse effect on streamflow because of increased evaporation and greater infiltration into groundwater. If the groundwater reservoir can be pumped, the loss of surface runoff may be offset. With the ever-increasing difficulty of reaching agreement on construction of new reservoirs because of environmental objections, the possibility of securing more complete regulation of river basin systems through construction of additional storage reservoirs in the West becomes increasingly remote.

Interbasin Transfers

Augmentation of water supply in one river basin through transfer of water from an adjacent river basin is a technique that has been used in the United States for more than two centuries, since water was imported from an adjacent basin to run a mill in the Charles River Basin in Massachusetts. In the past century more than a hundred interbasin transfers have been accomplished, some of which move substantial quantities of water. In the eastern part of the United States, the cities of Boston and New York depend on water supplies from adjacent basins for part of their drinking water. The Chicago River diversion from Lake Michigan, which reversed the flow of a river, transfers over 2 million acre-feet a year from the Great Lakes to the Mississippi River for pollution abatement. In the West, interbasin transfers are even more prevalent. Los Angeles went to the Great Basin for part of its water supply more than sixty years ago, to the Colorado Basin some forty years ago, and to the Sacramento River Basin in more recent years. Denver went across the continental divide to the Colorado River via the Moffat Tunnel for part of its water supply more than fifty years ago.

As the federal government assumed a larger role in U.S. water development, the scale of interbasin transfers increased, with irrigation a major purpose to be served. Projects such as the Colorado–Big Thompson diversion in Colorado and the Central Valley project in California were begun in the 1930s. It is ironic that the Colorado River Basin, which drains some of the nation's more arid areas and has the lowest run-off per square mile of any major river basin, is the exporting basin for such a large number of interbasin transfers. In addition to those already mentioned, the San Juan-Chama diversion in New Mexico, the Frying Pan–Arkansas project in Colorado, and the Central Utah project in Utah convey or will convey a substantial part of the Colorado River Basin runoff into other water resources regions. In a report published in the *Geographical Review,* Volume 58, pp. 108–132, Frank Quinn has tabulated 146 interbasin transfers in the western United States as of 1965 that transfer a total of more than 18 million acre-feet per year.

Starting with proposals made in 1950 in the Bureau of Reclamation's United Western Study, preliminary studies were made of even larger interbasin transfers until a moratorium on such studies by federal agencies was legislated in 1968. A summary of these developed by C. C. Warnick and published by the University of Arizona in *Arid Lands in Perspective,* 1969, is included as Table 2. The last project shown on the table is the Texas Water Plan, studied by the Bureau of Reclamation and the Corps of Engineers under a special Congressional authorization between 1967 and 1973. This proposal would have transferred over 10 million acre-feet annually from the Mississippi River or its tributaries to the high plains of Texas and New Mexico to sustain agricultural production after the Ogallala aquifer is pumped out. Cost of water delivered on the high plains was estimated to be well over $300 an acre-foot with the cost of energy for the 5,000-foot pump lift computed at pre-1973 price levels. Since that report was completed there has been less interest in interbasin transfers.

It is dubious whether any of these plans involving diversions across state lines can be undertaken, even if funds for construction could be made available. No state will be willing to sell its water "birthright" unless the consideration is so high as to increase the cost of the project to such an extent that it would not be economically justified.

International water transfers might have some possibility of being effected if the benefit from water development in the exporting country, which would be Canada, could be made high enough, and since the water for export would probably always flow north into the Arctic unused. However, the environmental disruption would be huge, and if the environmental movement develops in Canada as it has in the United States, it would be very difficult to negotiate the necessary treaty and enact the implementing legislation in the two countries.

Groundwater Management

There are an estimated 180 billion acre-feet of water in underground aquifers within a depth of 2,500 feet under the forty-eight contiguous United States. About one-fourth of this, 46 billion acre-feet, is usable with present technology; this is

TABLE 2
Summary of Information on Conceptual Plans Proposed for Regional Water Transfer

Project Name	*Agency/Company* Sponsor Author of Plan	Approximate Date of Proposal	River *Basin(s)* for Source	River *Basin(s)* of Use	Countries Involved	States Involved	Proposed *Diversion*. (a) 10^6 *acre-ft/yr*; (b) *cfs*, (c) *mgd*
United Western	U.S. Bureau of Reclamation Rep. R. J. Welch—Calif.	1950	Columbia River North Pacific Coastal Streams	Great Basin South Pacific Coastal Plain Colorado River	United States Mexico	11 Western States	6 0 9,100 5.900
California Water Plan	California Department of Water Resources	1957	Northern California Rivers	Central Valley California South Pacific Coastal Plain	United States	California	
Pacific Southwest Water Plan	U S Bureau of Reclamation W. I. Palmer	1963	Northern California Streams Colorado River	Lower Colorado River South Pacific Coastal Plain	United States Mexico	California Arizona, Nevada Utah, New Mexico	1.2 1,660 1,070
Snake-Colorado Project	Los Angeles Department of Water & Power S. B. Nelson	1963	Snake River	Colorado River South Pacific Coastal Plain	United States Mexico	Idaho, Nevada Arizona California	2.4 3,320 2,140
North American Power & Water Alliance (NAWAPA)	Ralph M Parsons Company	1964	Alaskan & Canadian Rivers, with Columbia River	Great Lakes Basin South Pacific Coastal Plain Colorado River Texas High Plains	United States Canada Mexico	Western States Texas Lake States	110.0 152,000 98,000
Yellowstone-Snake-Green Project	T. M. Stetson Consulting Engineer	1964	Yellowstone River Snake River	Green River Colorado River	United States	Montana, Idaho Wyoming, Lower Colorado States	2.0 2,770 1.780

TABLE 2 (continued)

Summary of Information on Conceptual Plans Proposed for Regional Water Transfer

Project Name	*Agency/Company Sponsor Author of Plan*	*Approximate Date of Proposal*	*River Basin(s) for Source*	*River Basin(s) of Use*	*Countries Involved*	*States Involved*	*Proposed Diversion (a) 10^6 acre-ft/yr; (b) cfs; (c) mgd*
Pirkey's Plan Western Water Project	F. Z. Pirkey Consulting Engineer	**1964**	Columbia River	Colorado River Sacramento River South Pacific Coastal Plain	United States Mexico	Oregon Washington California Utah, Arizona Nevada	15.0 20,800 13,400
Dunn Plan Modified Snake-Colorado Project	W. G. Dunn, Consulting Engineer	**1965**	Snake & Columbia Rivers	Great Basin Snake River South Pacific Coastal Plain Colorado River	United States Mexico	Idaho, Oregon Washington Utah, Arizona Nevada California	5.0 6,900 4,450
Sierra-Cascade Project	E. F. Miller, Consulting Engineer, Maryland	**1965**	Columbia River	Oregon Valleys Central Valley, California South Pacific Coastal Plain	United States	Oregon, Nevada California	7 0 9,700 6,250
Undersea Aqueduct System	National Engineering Science Company F. C. Lee	**1965**	North Coast Pacific Rivers	Central Valley South Pacific Coastal Plain	United States	Oregon California	11.0 15,200 9,800
Southwest Idaho Development Project	U.S. Bureau of Reclamation, Region 1	**1966**	Payette River Wetser River Bruneau River	Snake River	United States	Idaho	
Canadian Water Export	E. Kuiper	**1966**	Several Canadian Rivers	Western States (indefinite)	United States Canada	All Western States	150.0 208,000 134,000

Central Arizona Project	U.S. Bureau of Reclamation	1948, 1967	Lower Colorado River Basin	Colorado River	United States Mexico	Utah, Nevada Arizona California	1.2 1,660 1,070
Central North American Water Project C3 NAWP	E. R. Tinney Washington State University, Professor	1967	Canadian Rivers	Great Lakes Entire Western States	United States Candda Mexico	Great Lakes Western States	150.0 208,000 134,000
Smith Plan	L. G. Smith Consulting Engineer	1967	Liard River McKenzie River	All river basins of 17 western states	United States Canada Mexico	17 Western States	40.0 55,500 35,750
Grand Canal Concept	T. W. Kierens Sudbury, Ontario	1965	Great Lakes and St. Lawrence River	Canadian rivers flowing to Hudson Bay	United States	Great Lake States	17.0 23,600 15,200
Beck Plan	R. W. Beck Associates	1967	Missouri River	Texas High Plains	United States	South Dakota Nebraska Kansas, Colorado Oklahoma, Texas	10.0 13,800 8,930
West Texas and Eastern New Mexico Import Project	U.S. Bureau of Reclamation & U.S. Corps of Engineers	1967 (1972 due)	Mississippi and Texas Rivers	High Plain of Texas and New Mexico	United States	Oklahoma, Texas New Mexico Louisiana	16.5 22.900 14,700

Source C. C. Warnick, "Historical Background and Philosophical Basis of Regional Water Transfer," in ***Arid Lands in Perspective,*** McGinnies and Goldman, Eds. (Tucson: The University of Arizona Press, 1969), pp. 340–351.

about thirty-five times the annual surface runoff. Annual recharge may approximate one billion acre-feet, more than twice the amount that can be stored in all the man-made reservoirs in the United States, but much of this spills out of the aquifers to become part of the surface runoff if the aquifers are not pumped.

Availability and magnitude of this resource are well understood by the water resources professions in the United States but are not too well understood by the layman. Over 20 percent of all the water withdrawals for use in the United States are from ground water, a quantity estimated by the U.S. Geological Survey in 1975 at **83** bgd. This is less than 10 percent of the estimated recharge capability of 900 bgd, so there would appear to be room for a considerable increase in the use of ground water in many areas of the United States. Not all areas are favorably situated for the use of groundwater, however, and some of the heaviest uses of groundwater, as shown in Table 1, are in areas where there is insufficient recharge to provide a sustained yield anywhere near the present demand. Furthermore, in some areas, pumping of groundwater results in a direct reduction of surface stream flow.

Capacity of aquifers could be increased by increasing their water holding capacity through fracturing rocks by blasting or underground explosions, or by creation of underground barriers to temporarily store water, restrict the rate of flow, or divert the water along more desirable paths. The advantages of using ground water aquifers to a greater extent are minimization of evaporation losses, decrease in adverse environmental effects of construction, lower cost than construction of surface storage facilities, and decrease in pollution hazards. While recharge of aquifers has been practiced with varying degrees of success for many years in many places, it is not always successful. Recharge wells tend to become clogged with silt, and aquifers may become polluted. Nevertheless, the prognosis for recharge of aquifers and increased use of ground water for augmentation of water supplies in the West is probably more favorable than development of surface supplies. More states are recognizing the interrelationships between surface and ground water, and policies are being adapted to provide for conjunctive management of water resources from the two sources, which is an essential step before full use can be made of ground water to augment present supplies.

Water Harvesting Through Land Management

Land management through control of vegetation on watersheds and along water courses can be an important tool in augmenting water supplies. Typically, from 25 to 100 percent of precipitation is lost through evaporation or transpiration near the point where it falls. By modifying vegetal cover on watersheds, replacing dense forest with grass and scattered trees, or replacing brush and shrubs with grass, present water supplies in some watersheds can be increased by 10 percent or more. The soil surface itself can be treated to increase infiltration or to increase runoff into collection areas; either technique might be beneficial in augmenting water supplies in some areas of the West.

Removal of phreatophytes—water-loving plants such as salt cedars or cottonwood trees whose roots reach all the way down to the ground water—is'another technique that can be used to increase usable water supplies. A number of projects having this objective have been undertaken along water courses in the Rio Grande and Lower Colorado River basins. Phreatophyte removal must be accompanied by substitution of other vegetal cover, to prevent erosion and environmental objections that can be expected if wildlife habitat is destroyed in the process. Removal of phreatophytes through chemical defoliation also may have adverse side effects..

Desalinization

Substantial amounts of research funds have been expended on desalinization technology since 1952 when the federal research program was initiated. A number of demonstration plants have been built and operated by the U.S. government, and a sizeable industry has been developed, dominated largely by European firms. Costs of distillation projects are high and going higher as energy costs increase. Efforts have been made to finance large scale dual purpose desalting plants, in which heat is used for electric power generation as well as desalting, but the economics, based on the distillation process, have not been favorable.

Recent advances in development of processes for desalting of brackish water have centered on the reverse osmosis process, which uses less energy. A large plant is being built on the lower Colorado River to improve the quality of the water delivered to Mexico under the 1945 U.S.-Mexico Treaty and subsequent agreements. The need for the project is still being debated and costs are expected to be at least three times higher than the estimates on the basis of which it was authorized.

While solar distillation would appear to show some promise of reduced costs, the immense area required and substantial construction cost of the facilities required offset the savings in cost of energy.

Coupling of a desalting plant with a geothermal resource of hot brine is a possibility and may prove economic in such areas as the Imperial Valley of California, which is underlain with an immense reservoir of saline water at high temperature. Geothermal heat would be used in a dual purpose plant to produce electric power and to produce fresh water from the brine.

Precipitation Augmentation

Meteorologists believe that only about 10 percent of the water in the atmosphere actually reaches the earth. Laboratory experiments conducted by Langmuir in 1946 established a scientific basis for concluding that under favorable circumstances precipitation can be increased by seeding clouds with silver iodide crystals. If precipitation could be increased at the times and the places where there is need for additional water supply, this would appear to be an extremely valuable technique for augmenting water supplies in the western United States.

The processes and potential of precipitation augmentation as a means of augmenting water supply are not yet fully understood. Research so far appears to have established that cloud-seeding techniques may be used to increase precipitation from winter orographic clouds (clouds that are forced upward as they pass over mountains) without significant adverse environmental effects. The additional snowfall produced creates problems in highway maintenance costs, increases danger from avalanches, and may decrease precipitation elsewhere, but the skiers should love it. A research and demonstration program conducted by the Bureau of Reclamation in the San Juan Mountains of southern Colorado over a four-year period led to the conclusion that seeding produced increases in precipitation of about 10 percent during a winter of average snowfall, with a resulting potential increase in the flow of the San Juan River of about 19 percent.

Progress toward developing a scientific basis for increasing precipitation from warm season convective clouds has been much slower, but many atmospheric scientists believe that we know enough to conduct a full scale field experiment. Environmental problems may be greater; too much rain in the summer months may have adverse economic effects. So far there is no way to show that increased precipitation in one area may not result in a decrease in other areas. An environmental impact statement based on the results obtained to date and the comments of concerned individuals, agencies, and interest groups has been filed, and the Bureau of Reclamation is continuing research in the high plains regions of Montana, Kansas, and Texas, with cooperation of the states and the universities. It may be decades before we know enough to be able to count on augmenting water supplies by artificially increasing precipitation.

Better Forecasting of Hydrologic Events

Research on precipitation augmentation may lead to increased knowledge of atmospheric processes that may make it possible to make better forecasts of both long- and short-term precipitation. Accurate forecasts could make it possible to manage reser-' voirs in such a way as to increase usable water supplies. Reliable and accurate short-term forecasts would permit use of flood-control storage for water conservation, while accurate long-term forecasts would permit modification of agricultural programs so as to decrease water demands and minimize drought losses.

Augmenting Fog Drip

When low-lying clouds or fog intercept the earth's surface, condensation of water occurs, and the ground and the vegetal cover becomes wet. This is sometimes referred to as horizontal pi-ecipitation, cloud condensation, or fog drip, and occurs naturally in many places, including the forests along the coastal shores and mountains of California and Oregon. An experiment in Hawaii consisting of planting Norfolk Island Pine trees on a cloud swept ridge on the island of Lanai in Hawaii has demonstrated that the technique may be useful. The estimated increase in water supply of 400 acre-feet annually is used for supplemental irrigation on pineapple plantations in neighboring valleys. Other development possibilities for the use of fog drip include planting crops under trees so the crops could utilize drip water, or using impervious surfaces under trees to collect the fog drip water for delivery to crops. More research into such techniques as inducing electrical charges in the fog particles and chemical seeding might develop more efficient ways to harvest water from fog drip.

Snow and Icefield Management

A number of techniques involving manipulation of snow and ice resulting from winter precipitation have been advanced. Application of snow melt retardants on high mountain snow fields might be useful in prolonging the period of spring runoff in many areas of the West. Deliberate avalanching of selected snow fields so as to create deep piles that would melt slowly late in the spring to meet water demands or to replenish reservoir storage might promote more efficient use of snow melt retardants, as they could be applied to a reduced area of denser snow. Care would have to be taken that the avalanche snow is not in a warmer area that would induce more rapid melting than at the unavalanched site. Likewise, it is necessary to insure that the avalanched snow does not block a live stream.

Creation of artificial ice fields has also been mentioned as a means of delaying spring runoff to augment usable water supplies during the late spring or summer. Water released from reservoirs on winter nights and sprayed onto shaded terraces or north-facing slopes would freeze as it falls, forming an ice field that would melt in the spring to augment water supply. If the water would have spilled anyway and been lost downstream, this would have the effect of increasing the yield of the reservoir, but in a fully controlled river system no new water supply would be created. Environmental impacts and costs have not been assessed.

Iceberg Towing

Discussion of snow and ice leads naturally to the subject of iceberg towing—capturing or quarrying floating icebergs.and towing them to a suitable offshore point where they could be broken up into manageable pieces that could be hauled on shore by a conveyor belt or other system to provide cooling and water supply. The technique has been much talked about but never put into practice. It has been ascertained that the icebergs from the Antarctic would be more suitable than those from the Arctic, since the latter are irregularly shaped because they come from mountain glaciers. This tends to make them dangerously unstable.

,Icebergs from the great Antarctic ice shelf tend to be larger and of a more regular shape so they can be more safely towed. Ocean currents that flow northward from the Antarctic continent also favor use of icebergs from the south, even though they would have to be towed across the tropics. It has been estimated that five or six of the largest tugboats could move an iceberg of 100 million tons at a speed of one knot with a loss of only about 20 percent of its volume, if suitable protection against erosion is provided.

An international conference on this subject held in October 1977 at the University of Iowa concluded that the problems posed were within the reach of existing technology and that water produced from icebergs would cost less than fresh water produced by desalinization. If the technique is to be tried it would appear that Saudi Arabia would be the logical place, as the needs are great and there are fewer alternative sources of water. Until such a test is made, there is little reason to look to towing icebergs as a means of augmenting the water supplies of the western United States.

Undersea Aqueducts

One of the potential sources of augmenting water supplies in southern California that was considered in the Bureau of Reclamation's United Western investigation was an undersea aqueduct carrying fresh water southward from the mouth of the Columbia River. The principle involves laying a large-diameter, flexible or semirigid plastic pipe leading from a pumping station at the source, which is at the mouth of the river, taking the water at a point where it is no longer of use to the basin of origin. The Bureau of Reclamation report concluded in 1950 that a conventional interbasin transfer would be more economical. Since then other proposals have been advanced, but they appear to be more in the realm of science fiction than that of a serious alternative source for augmentation of water supply in the West.

Collapsible Bladders for Transport of Liquids

Petroleum products can be transported through waterways and the sea by using large watertight bags or bladders fabricated of synthetic rubber or some type of plastic film. The same technique could be used with water. The empty bladder could be easily transported to a place where there is an 'excess of fresh water, immersed, and loaded with fresh water, then towed by ship to the point where the water is needed. Such a method might be used to provide for reuse of some of the vast quantities of fresh water that flow out to sea from the mouth of the Columbia River.

Evaporation Reduction

The possibility of increasing water yield by controlling evaporation from land surfaces has been touched on briefly earlier in this paper. Similar results could be achieved through spreading a layer of an insoluble chemical coating, such as hexadecanol, on reservoirs. The technique is not effective in areas of high winds that break up the layer or drive it up on the shore. At the time extensive tests and research were conducted by the Bureau of Reclamation, it appeared that the cost of the treatment was equal to or greater than the value of the water saved.

Demand Reduction

Thoughtful consideration of the alternatives discussed heretofore tends to lead one to the almost inescapable conclusion that the most economical solution to the problem of satisfying demands, at least over the near term, is demand reduction. All of the methods heretofore discussed involve costs, both economic and environmental. On the other hand, some forms of demand reduction actually create savings. Savings in pumping costs and savings in pipe sizes and the size of the facilities are a few of the obvious ways in which savings may accrue. Savings may be offset by the cost of the more careful engineering and more intensive water management techniques that may be required.

Pricing

Water has been so abundant that it was assumed in the past to be a "free good" available for the taking. The importance of water availability as a stimulus to the economy has led to subsidies that were deemed to be necessary to achieve various social purposes, such as the encouragement of development in the West. The time has come for the need to subsidize the price of water for agriculture to be reexamined. Pricing of water at levels which repay costs of development in full would be a powerful stimulus to more efficient use of water and reduction in demand.

Water Reuse

Rising costs and increasing environmental regulation have led to an increase in recycling and reuse of water in industrial plants. This stretches the use of existing water supplies and reduces demand for new supplies. The use of effluent from municipal sewage treatment plants for industrial purposes is quite prevalent in the East, and extension of the practice in the West could reduce demands for development of new supplies. A demonstration project right here in Denver is pointing the way.

Recycling of effluents back through the primary drinking water system cannot be recommended at this time and does not appear to be necessary yet. Research is under way that should clear up some of the unknown questions about what happens to the pathogenic bacteria and viruses and other impurities which may persist through the treatment process. At some time in the future, it may be possible to reuse and recycle some of the water that now passes once through the municipal systems, thus effecting a substantial reduction in demand.

Increased Efficiency in Irrigation

Experience with some crops during the California drought a few years ago showed that yields actually increased when a smaller amount of water was applied. While this is not a condition of general applicability for most crops, it is true that there are many instances in which irrigation diversion can be reduced. For example, the flooding of high mountain meadowland to create forage for livtstock may result in unnecessary evaporation losses. Application of irrigation water under controls related to soil moisture conditions, rather than water rights, also might result in savings. Very specialized techniques, such as trickle irrigation, are also available, but at a considerable cost. As water shortages in the West become more prevalent, we can expect some reduction in demand of water for irrigated agriculture, if our institutions can be updated to meet the new conditions.

Improved Institutions for Allocating Water

This subject is to be discussed by several speakers at the Friday morning session, so it will not be covered here.

Conclusion

In the available time it has been possible to touch only briefly on the many ways of augmenting water supplies in the western states. A great deal of additional research is underway that has not been possible for me to assimilate in the available time. No attempt has been made to compare the costs of various alternatives for augmenting supply or reducing demand, since the estimates contained in the literature are based on different assumptions, not always clearly stated. On the basis of my experience, I would reiterate my view that the most economic way to bring supply and demand into balance is by reducing demand.

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