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Water Use in Agriculture Now and for the Future

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Summary

Water is the primary limiting factor in agriculture in the United States and the world. The western states have gained importance in agricultural production only through extensive use of irrigation from surface and groundwater sources. With the increase in population, these water supplies are facing new pressures for reallocation. Accurate scientific information concerning water availability, behavior, management, and value is essential in optimizing water allocation on farms, in agriculture, and among agriculture and the various other uses. This report is an overview of the physical, institutional, economic, and sociological aspects of the water issue from the standpoint of agriculture. It is intended to provide basic understanding for those who are concerned with the big picture.

Essentially all of the water used in the United States is derived from precipitation. A portion of the precipitation flows to streams, ponds, lakes, and reservoirs, and some of this eventually reaches the oceans; another portion infiltrates the soil to the rooting zone; and another portion percolates below the rooting zone and becomes groundwater. Surface sources of water are recharged rapidly, but groundwater reservoirs (aquifers) are recharged only slowly in dry regions. Aquifers in some dry regions are being exhausted by pumping. The proportion of the precipitation received in the United States that is returned to the atmosphere as water vapor is estimated to be 70% from nonirrigated land areas and 2% from irrigated areas. Most of this loss represents evaporation or transpiration from plant surfaces.

Plants use far more water than is required in the vital processes of growth and development. This inefficiency is largely a consequence of stomatal apertures in the foliage through which water vapor leaves the plants. Although vaporization of water is important in cooling the leaves, loss of water vapor is not an essential function as such. Rather, it can be considered a necessary evil that accompanies absorption of atmospheric carbon dioxide through the same openings for the essential process of photosynthesis. The stomata close when the water supply is deficient, and this decreases the transpiration, but it also decreases photosynthesis.

Water is essential also in animal production. The total agricultural use of water, however, is so heavily dominated by plants that the amount required in animal agriculture is of only minor concern.

Salinity is the most serious water-quality problem in agriculture. When water evaporates from the surface of the soil or the surfaces of plants, the dissolved salts are left behind. The salts build up in the soil and eventually prevent plant growth if they are not removed by leaching them below the root zone. Water quality is important in animal agriculture, but here the principal concern is for toxicants.

Irrigated cropland harvested amounted to 14% of the total acreage harvested in the United States in 1978, but the value of these crops amounted to 36% of the total value of all crops produced. About 85% of the irrigated land is located in the 17 western states, and in 9 of these states more than 50% of the total acreage of harvested crops is irrigated. All states have periods of low rainfall in which irrigation is needed, however, and irrigation is gradually increasing in the eastern states. The extreme example, Florida, is in a high-rainfall area, but more than 50% of the total value of the crops it produces is derived from irrigated crops.

Water for irrigation commonly is stored in surface reservoirs or aquifers and is applied as near to the time it is needed as the facilities will permit. Application methods include surface systems, in which the water flows on the soil; sprinkler systems; and drip systems, in which the water is distributed through plastic tubes with small holes through which the water drips on or in the soil. New equipment and new technology have enabled farmers to increase the ratio of crops produced to irrigation water delivered, and further improvements are possible.

Various procedures for increasing the supply of water for agriculture are technologically feasible. Reuse of water from municipal sources and from irrigation return flows is widely practiced at present. Reuse of treated water from municipal, industrial, and electrical generation sources is expected to account for a small but increasing portion of the supply of water to agriculture in the future. Desalination of brackish water is too expensive for practical use at present, and cloud seeding requires further development before it will be ready for general use. Removal of "nonbeneficial" vegetation that has high water requirements, snow management, runoff management, and changing the landscape to direct water to limited areas are other procedures that have some practical use.

Many possibilities exist for conserving existing supplies of water for irrigation, but the savings from individual techniques generally are small. Realizing the potential would be difficult in practice.

The institutional development in irrigation is extensive. Some 35 federal programs in 10 separate agencies provide some type of assistance to irrigation. Most states have an impressive array of agencies relating to water resources. Local agencies consist of water districts and conservancy districts which are established to perform a service, usually that of supplying water for various uses. Many different kinds of organizations, governmental and otherwise, deliver water to farmers.

In water law, there are two doctrines of water capture
Introduction

Water is a renewable and essentially indestructible resource, but it is the most limiting factor in both U.S. and world agriculture. The principal physical problems are caused by erratic supplies that are generally deficient over large areas, occasionally or frequently deficient in most other areas, and sometimes locally excessive. In some areas, poor quality (excessive salinity) and depletion of groundwater reservoirs are of concern.

In the United States, water is especially deficient in the West. The western states gained their principal importance in agriculture only through extensive use of surface and groundwater sources for irrigation. Agriculture consumes far more water than all other human uses combined, and there is no practical way to change this situation, although agricultural water use can be made more efficient than it is at present.

The deficiencies of water and its indispensability for many purposes have given rise to serious human conflicts over water use and allocation. Disputes over water are not new in America, and in the West they have been almost a way of life. With the increase in population in the West, there is increasing competition for water, and water supplies are facing new pressures for reallocation.

Accurate scientific information concerning water availability, behavior, management, and value is essential in optimizing water allocation on farms, in agriculture, and among agriculture and the various other users. This report includes within a few pages an overview of the physical, institutional, economic, and sociological aspects of water use in agriculture, as well as a brief review of some of the current controversial issues. The report is intended to serve as background for those who are interested in the big picture.¹

Water — A Natural Resource

Water supply is regulated by the hydrologic cycle illustrated in Figure 1. Local occurrence, quantity, and quality can be modified to some degree, but water is not destroyed to a significant extent by human activity. Surface water is available in a predictable range, and supplies are renewed rapidly. Surface water is a renewable resource. Groundwater reservoirs or aquifers similarly may be considered a renewable resource in regions in which precipitation considerably exceeds evaporation unless the overdraft is heavy and fairly continuous. In dry regions, however, water stored in aquifers that are not along stream channels or other sources of excess surface water is replenished at such a slow rate that such water is essentially a nonrenewable resource.

Water Supply

Essentially all of the water used in the United States is derived from precipitation. Through complex atmospheric processes, water is evaporated, condensed to form clouds, and transported by wind; ultimately it appears as precipitation. A portion of the water falling on the land flows to fresh-water streams, ponds, and lakes; another portion infiltrates the soil to the rooting zone; and another portion percolates below the rooting zone to the groundwater.

Average annual precipitation patterns for the United States are shown in Figure 2. East of the Rocky Mountains, the average precipitation increases as one moves away from the mountains; the intermountain region of western United States has higher average precipitation than the Great Plains; and, in the states which border the Pacific Ocean, the annual precipitation decreases from north to south.

Seasonal distribution of rainfall is greatest in the summer in the central United States, providing rain during the period of greatest need by crops. In agricultural areas of California, rainfall occurs almost entirely during the winter, making these areas highly dependent upon water stored to meet crop water needs during the summer.

In all regions, precipitation varies from place to place and from year to year. For example, in central Missouri the total rainfall in June has been as low as one inch and as great as 10 inches. Periods of years with abundant rain may be clustered, whereas periods with drought, such as during the thirties and fifties in the central United States, often extend for a half decade or more.

Geographic areas may be classified according to their long-term average water balance. Humid and subhumid regions are those in which precipitation exceeds evapo-

¹A document entitled “Weather and Water Allocation Study” by Ahalt et al. (1979) reviews the water allocation issue with emphasis upon the meteorological aspects of the subject. The document includes a chapter called “Water Laws and Administration” that reviews some of the same subject matter covered in this report under “The Institutional System.”
and use. According to the “riparian doctrine,” the owner of private land along a stream has the right to use the water provided that the use does not interfere unreasonably with the rights of persons who own other parts of the stream or with the rights of adjacent owners. According to the “prior appropriation” doctrine, a “water right” is acquired by diverting water from a water course for a beneficial use. The first person to appropriate the water and put it to reasonable and beneficial use has a right superior to any later appropriators. In the western states, water laws generally are based upon the doctrine of prior appropriation. Some eastern states have established a permit system for managing their water resources, and others are considering it. The permit system is essentially a modified appropriation doctrine.

Control of groundwater utilization has been difficult. Various states have adopted one or more of four different doctrines: (1) absolute ownership of water under the land; (2) reasonable use, which recognizes the right of all to the resource; (3) correlative rights, in which the landowner must correlate his use with others; and (4) the doctrine of prior appropriation, in which the groundwater is the property of the state and is subject to appropriation.

The statutes establishing the legal basis for water rights law in the West were enacted when the demand for water was much less than it is now. Rights to utilize water for irrigation were granted to prospective users to give them the security of continued use to induce investment for stability and profitability. Continued development of the West has resulted in increased demand for water, and water-allocation problems consequently have become important. One of the problems has been that there is limited economic incentive to invest in conservation practices and structures, and this has led to less emphasis on water conservation on farms, in households, and in factories than might otherwise be expected.

As the competition for water intensifies, more attention will be devoted to devising new mechanisms for allocating water among competing uses and to modifying existing mechanisms. For the most part, institutional barriers have inhibited transfers of water. Results of studies now suggest that the current environment requires mechanisms which facilitate the transfer or reallocation of water among competing uses. The fundamental change required to facilitate transfer or reallocation is a system of laws or rules allowing voluntary exchange of water rights while protecting the interests of third parties.

In agriculture, a commonly expressed argument against relaxing the institutional barriers that inhibit transfer of water rights is that higher valued uses would take too much of the water now used for agriculture. A recent study does not support this view. The limited experience available suggests that market-like mechanisms for transferring water work well.

In the future, the agricultural industry will be held more closely accountable for the way it uses water than it has in the past. Agriculture will have to expend more effort to justify its claims to water, particularly under scarcity conditions, and will have greater responsibility for the environmental impacts of the water it uses and returns to the system.

Numerous aspects of water use and availability are controversial and have not yet been resolved. Some of the more prominent issues in which policies currently are of concern are: (1) Incentives to encourage water conservation practices. (2) Incentives to encourage control of soil erosion, which now degrades the quality of both soil and water. (3) The policy decision to protect the quality of surface water by reducing the allowable discharge of salts into drainage water, which assures the buildup of salts in the groundwater and the soil and increases the hazard of crop damage by excessive soil salinity. (4) Control of groundwater depletion. (5) The legal and administrative doctrines and rules controlling water rights, which now make it difficult or impossible for the owner of an irrigation water right to transfer it to potential users whose use of the water may have higher economic value. (6) The extent to which interbasin transfers of water should be rationalized on economic grounds and on noneconomic considerations. (7) The extent to which the prices charged for water and water-related services should reflect their cost, and the extent to which use restraints should be put into effect so that allocation of water use by the market mechanism will assure that the social benefits will be positive. (8) The limitation that currently exists on the acreage that can be irrigated with federally developed water. (9) The extent to which the direct beneficiaries of federally developed water should be required to bear the development and operating costs. (10) The extent to which competitive interest rates should be charged to local and state agencies by the federal government for funding water development projects. (11) The impact upon water use of government policies that seemingly are unrelated to water. (12) The potential consequences of widespread usage of techniques to increase precipitation.
transpiration. The average position of the boundary between the subhumid and semiarid regions, although varying from year to year, extends in a generally north to south direction across the eastern Dakotas, east central Nebraska, Kansas, and Oklahoma, into Texas. Rainfall deficits may occur in humid regions for periods of weeks or even months. In arid and semiarid regions, precipitation usually is not sufficient to satisfy the demand for evapotranspiration. Crops are grown in these areas during only part of the year or are irrigated with water from streams and aquifers.

2Evapotranspiration is the combined loss of water by evaporation from the soil surface and by transpiration from the plant canopy. Potential evapotranspiration is the evaporation of water from a soil surface and transpiration from an actively growing complete plant canopy when there is adequate soil water.

Surface Water

Surface water, derived mostly from runoff, occurs in rivers, streams, swamps, and impoundments. Figure 3 provides estimates of average annual runoff in the United States. The volume of surface water runoff varies greatly from day to day, season to season, and region to region. Within a normal year in a given region, the maximum stream flow may be 500 times greater than the minimum. The range from year to year generally is smaller than this, and the range in humid regions generally is smaller than it is in arid regions.

The storage capacity of all large manmade reservoirs in the United States totals approximately 450 million acre feet (MAF) (Table 1). Thirty-one large reservoirs with a capacity of more than 2 MAF have a combined storage capacity of 191 MAF, 41% of the total storage. Small reservoirs, such as farm ponds used for water supply, fire protection, and recreation, number over 1.8 million and store only 10 MAF or 2% of the total.
Groundwater

In the 48 conterminous states, about 86% of the water resources are located in groundwater reservoirs or aquifers which vary in thickness. Figure 4 shows the location of the major aquifers.

Groundwater is the source of about 20% of the fresh water utilized in the United States, and its use has been increasing at an annual rate of 3.8%. Of the total groundwater withdrawal, the 68% used for irrigation is 35% of the water used for that purpose (U.S. Water Resources Council, 1978).

Surface and groundwater often are interconnected. Hence, a withdrawal from one can affect the level of the other. About 30% of the nation's streamflow is supplied by groundwater that seeps to the surface (U.S. Water Resources Council, 1978). Quality of water (surface and groundwater), therefore, can be affected by seepage from one source to the other.

Aquifers are replenished or recharged by downward percolation of water. In some areas, however, the withdrawals (primarily for irrigation and municipal supplies) are greater than the rate of recharge. The water level or

<table>
<thead>
<tr>
<th>Size Class</th>
<th>Number</th>
<th>Total Capacity, Million Acre Feet</th>
<th>Percent of Total Capacity of all Reservoirs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 50 acre feet</td>
<td>1,800,000</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>50 to 5000 acre feet</td>
<td>47,500</td>
<td>90</td>
<td>20</td>
</tr>
<tr>
<td>5001 to 2,000,000 acre feet</td>
<td>1,600</td>
<td>159</td>
<td>37</td>
</tr>
<tr>
<td>More than 2 million acre feet</td>
<td>31</td>
<td>191</td>
<td>41</td>
</tr>
<tr>
<td>Total</td>
<td>1,849,131</td>
<td>450</td>
<td>100</td>
</tr>
</tbody>
</table>
water table consequently is falling, and the aquifer is said to be "overdrawn" or "mined." For example, in the Texas-Oklahoma High Plains, the overdraft is about 14 MAF annually (equivalent to 12.5 billion gallons per day).

In areas with continuing mining of groundwater, pumping eventually will become uneconomic (U.S. Water Resources Council, 1978), and serious economic and social consequences will result. Sloggett (1981) reported that groundwater levels are declining from 6 inches per year to more than 6 feet per year in areas in the 11 states in which pump irrigation is important. According to his analysis, irrigated areas in the Texas High Plains are expected to decrease as much as 50% by the year 2020, largely because of a depleted aquifer, but in the United States in general the area irrigated is not expected to decrease significantly from declining groundwater levels until well into the next century. Energy costs for irrigation are a major cause of uncertainty. He pointed out that costs of electrical energy for pumping on the Texas High Plains increased $4 per acre foot per year from 1973 to 1979 and that only 20 cents of this annual increase resulted from the declining water level.
Figure 4. Major aquifers in the United States (U.S. Water Resources Council, 1978).
Withdrawals and Consumptive Uses

Some uses of water, called “instream,” do not require diversion from a river or reservoir for use elsewhere. These include navigation and hydropower uses as well as flows maintained for environmental purposes, such as maintenance of fish or wildlife, scenic attractions, or water quality. Although instream uses do not require withdrawal of water for use elsewhere, they may nonetheless result in wastage of water if users or uses do not require the water at the rate at which it arrives.

The major part of the water withdrawn from surface and underground sources for most domestic and manufacturing purposes remains in the liquid form and may be used again for the same or other purposes. The major part of the water withdrawn for agricultural purposes is used for irrigation, however, and most of this water normally is changed to the vapor phase by evapotranspiration and cannot be reused until it is returned to the earth in precipitation.\(^3\) Uses in which the water becomes a part of the product or that result in return of the water to the atmosphere as a vapor are termed consumptive uses.

The total amount of fresh water withdrawn in 1975 from all sources for all uses, including agricultural, domestic, commercial, manufacturing, mineral production, power generation, and maintenance of public lands, was estimated by the U.S. Water Resources Council (1978) at 379 MAF (Table 2). By the year 2000, fresh water withdrawals are projected to decrease to 343 MAF, a 9% reduction from 1975 (Table 3). This decline reflects aquifer depletion as well as economic forces, changes in technology, and changes in water management, including reuse and conservation.

Use of Water in Agriculture

Table 3 shows that the total withdrawal of water by agriculture is projected to decrease from 180 MAF in

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\(^3\)&nbsp;According to Wolman (1962), the amount of water withdrawn from streamflow and aquifers for irrigation is equivalent to 3.4% of the annual precipitation received in the 48 conterminous states, and 60% of this amount is estimated to be lost to the atmosphere. According to the same source, 70% of the annual precipitation received in the United States is lost to the atmosphere as water vapor from nonirrigated land areas. The distribution of the 70% was estimated at 23% from farm crops and pasture, 16% from forests and browse vegetation, and 32% from noneconomic vegetation.

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Table 2. Estimated Fresh Water Withdrawals in 1975 (U.S. Water Resources Council, 1978)

<table>
<thead>
<tr>
<th>Water Resource Region</th>
<th>Surface Water</th>
<th>Ground Water</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>New England</td>
<td>4.99</td>
<td>0.71</td>
<td>5.70</td>
</tr>
<tr>
<td>Mid-Atlantic</td>
<td>17.52</td>
<td>2.98</td>
<td>20.50</td>
</tr>
<tr>
<td>South Atlantic-Gulf</td>
<td>21.35</td>
<td>0.10</td>
<td>21.45</td>
</tr>
<tr>
<td>Great Lakes</td>
<td>46.59</td>
<td>1.36</td>
<td>47.95</td>
</tr>
<tr>
<td>Ohio River</td>
<td>37.06</td>
<td>2.06</td>
<td>39.12</td>
</tr>
<tr>
<td>Tennessee River</td>
<td>8.00</td>
<td>0.30</td>
<td>8.30</td>
</tr>
<tr>
<td>Upper Mississippi River</td>
<td>11.24</td>
<td>2.65</td>
<td>13.89</td>
</tr>
<tr>
<td>Lower Mississippi River</td>
<td>10.90</td>
<td>5.42</td>
<td>16.32</td>
</tr>
<tr>
<td>Souri-Red-Rainy Rivers</td>
<td>0.28</td>
<td>0.10</td>
<td>0.38</td>
</tr>
<tr>
<td>Missouri River</td>
<td>30.92</td>
<td>11.66</td>
<td>42.58</td>
</tr>
<tr>
<td>Arkansas-White-Red Rivers</td>
<td>4.50</td>
<td>9.19</td>
<td>13.69</td>
</tr>
<tr>
<td>Texas-Gulf</td>
<td>10.87</td>
<td>8.09</td>
<td>18.96</td>
</tr>
<tr>
<td>Rio Grande River</td>
<td>4.46</td>
<td>2.62</td>
<td>7.08</td>
</tr>
<tr>
<td>Upper Colorado River</td>
<td>7.55</td>
<td>0.14</td>
<td>7.69</td>
</tr>
<tr>
<td>Lower Colorado River</td>
<td>4.38</td>
<td>5.61</td>
<td>9.99</td>
</tr>
<tr>
<td>Great Basin</td>
<td>7.36</td>
<td>1.59</td>
<td>8.95</td>
</tr>
<tr>
<td>Pacific Northwest</td>
<td>33.76</td>
<td>8.23</td>
<td>41.99</td>
</tr>
<tr>
<td>California</td>
<td>22.92</td>
<td>21.46</td>
<td>44.38</td>
</tr>
<tr>
<td>Alaska</td>
<td>0.29</td>
<td>0.05</td>
<td>0.34</td>
</tr>
<tr>
<td>Hawaii</td>
<td>1.22</td>
<td>0.88</td>
<td>2.10</td>
</tr>
<tr>
<td>Caribbean</td>
<td>0.73</td>
<td>0.28</td>
<td>1.01</td>
</tr>
<tr>
<td>Total</td>
<td>286.09</td>
<td>92.20</td>
<td>379.09</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Functional Use</th>
<th>Fresh Water Withdrawals, Million Acre Feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic</td>
<td>26.05</td>
</tr>
<tr>
<td>Commercial</td>
<td>6.19</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>57.37</td>
</tr>
<tr>
<td>Agriculture</td>
<td>177.79</td>
</tr>
<tr>
<td>Irrigation</td>
<td>2.14</td>
</tr>
<tr>
<td>Livestock</td>
<td>98.59</td>
</tr>
<tr>
<td>Power Generation</td>
<td>7.90</td>
</tr>
<tr>
<td>Mineral Production</td>
<td>2.08</td>
</tr>
<tr>
<td>Public Lands and Other</td>
<td>379.12</td>
</tr>
</tbody>
</table>
1975 to 175 MAF in 2000, but the total consumptive use is expected to increase from 99 MAF to 106 MAF. Irrigation accounted for 81% of the total consumptive use of water withdrawn for all functions in 1975 and is expected to be responsible for 68% in 2000.

As indicated by Table 3, the water withdrawals and consumptive use for agriculture are dominated by irrigation. Water use in animal agriculture represents less than 3% of the total. The disparity between crop production and animal production is even greater than that which may be inferred from the table because the figures for livestock represent totals for the United States and not totals for the minor portion of the livestock associated with crops produced under irrigation. According to data in Figure 1 and Footnote 3, the total annual consumptive use of water by nonirrigated crops and pasture in the United States is about 1080 MAF.

**Role of Water in Plants**

Most of the water used by cultivated crops is absorbed through the roots and then is transported through the roots and stems to the leaves and fruits. As much as 90% of the fresh weight of plants may be water. Water is lost continually from plants by evapo-
The arrows in these photomicrographs point to the microscopic pores or stomates in a bean leaf through which water and carbon dioxide move as gases. In A, the stomate is open. The two "guard" cells that form the boundary of the stomate are turgid as a result of an ample water supply in the leaf. In B, the two guard cells are flaccid as a result of water deficiency in the leaf, and this has resulted in closure of the stomate. Stomatal closure greatly reduces the loss of water vapor from plants, but it reduces also the entry of the atmospheric carbon dioxide required for photosynthesis and plant growth. Photographs courtesy of the U.S. Department of Agriculture.

Evapotranspiration

Energy from solar radiation plus that carried by dry air moving over vegetated areas is responsible for evapotranspiration. Evaporation from the soil can be nearly equal to the transpiration from plant surfaces if the soil surface is bare and moist. The soil surface usually dries within a few days after irrigation or rain, however, and the rate of evaporation from the soil then is much reduced. After the soil surface is dry, most of the loss of water normally occurs by transpiration from plant surfaces.

The amount of water absorbed by plant roots and transpired from plant surfaces is influenced by soil, plant, and atmospheric factors. Soil factors affecting
water uptake by roots include available soil water, aeration, salt content, and temperature. Plant factors include the depth, branching, permeability, and conductivity of the root system as well as the length of time it takes the crop to mature. Morphological features of leaves that may reduce transpiration include hairiness, waxy surfaces, stomatal closure, and stomatal size, number, and location on leaf surfaces. Stomatal closure is the most effective. Atmospheric factors that affect the amount of water absorbed by plant roots and transpired from plant surfaces include temperature, solar radiation, relative humidity, and wind velocity.

About 50% of the solar energy reaching plant surfaces is dissipated through transpiration. The amounts of water transpired by plants greatly exceed the amounts required for normal plant growth processes such as photosynthesis, metabolism, and cell division and enlargement.

Evapotranspiration from fields of continuously growing plants in arid regions of the Southwest can be as great as the equivalent of 5 feet of water per year. In the northern states, the requirements are no more than half as great (Todd, 1970). Table 4 shows a few measured values of evapotranspiration for different crops. The several values for sugarbeet have been included to illustrate the range that may occur with environmental conditions. The values for corn, potatoes, and grapefruit have been included to illustrate the range that may occur at a given location. Grapefruit is a perennial, evergreen crop that was irrigated all year at Phoenix, Arizona. Potatoes, also at Phoenix, Arizona, used only half as much water as grapefruit but were irrigated only one-third as long, so that the rate per day actually exceeded that for grapefruit, as calculated from the data for the entire year. In general, an annual crop would be expected to use less water than a similar, established perennial crop during the period of growth of the annual crop because annual crops use relatively little water during the time of establishment.

In humid regions, evapotranspiration usually is less from cropland than from native vegetation. Cropping, particularly to row crops, increases the supply of both surface and ground water. The principal reasons are that (1) runoff of water generally is greater from cropland than from land under native vegetation, and (2) native vegetation usually consists of a mixture of plant species that withdraws water from the soil throughout the frost-free season (some species even after herbaceous plants have been frozen), whereas in agriculture much of the cropland is planted to annual crops that result in fallow periods in the spring before planting and in the fall after harvest.

A basic problem in transpiration reduction is the fact that the stomatal openings in leaves, through which most of the transpiration occurs, are also the avenue through which land plants absorb from the air the carbon dioxide they use in photosynthesis. Transpiration thus may be considered a necessary evil as far as productivity of land plants is concerned. Transpiration retardants are effective in reducing plant transpiration rates, but they interfere with carbon dioxide intake as well as transpiration and, hence, generally reduce crop yield.

Table 4. Evapotranspiration by Irrigated Crops During the Irrigation Season in the Western United States (Jensen, 1974)

<table>
<thead>
<tr>
<th>Crop</th>
<th>Location</th>
<th>Irrigation Season</th>
<th>Evapotranspiration During the Irrigation Season, Inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugarbeet</td>
<td>Huntley, Montana</td>
<td>April 20-Sept. 27</td>
<td>22.5</td>
</tr>
<tr>
<td>Sugarbeet</td>
<td>Garden City, Kansas</td>
<td>April 10-Nov. 1</td>
<td>36.5</td>
</tr>
<tr>
<td>Sugarbeet</td>
<td>Bushland, Texas</td>
<td>May 28-Oct. 18</td>
<td>39.0</td>
</tr>
<tr>
<td>Corn</td>
<td>Bushland, Texas</td>
<td>May 7-Sept. 8</td>
<td>24.3</td>
</tr>
<tr>
<td>Potatoes</td>
<td>Phoenix, Arizona</td>
<td>Feb. 15-June 15</td>
<td>24.3</td>
</tr>
<tr>
<td>Grapefruit</td>
<td>Phoenix, Arizona</td>
<td>12 months</td>
<td>47.9</td>
</tr>
</tbody>
</table>
An efflorescence of soluble salts causes the light-colored areas on this soil along the Chalk Creek in Utah. Most of the excesses of soluble salts that occur in soils result from the gradual weathering or decomposition of the minerals present in soils. The salts become concentrated gradually as a result of movement of water from locations of higher elevation to those of lower elevation, followed by evaporation of the water. Accumulation of salts can be very rapid when irrigation is practiced, because irrigation waters contain salts, and large amounts of water may be used. The rainfall is sufficient to wash the excess salts out of the soil in humid regions but not in dry regions. Photograph courtesy of the Soil Conservation Service, U.S. Department of Agriculture.

(Davenport et al., 1977). Genetic modification of plants may offer some possibility for increasing water-use efficiency by increasing photosynthetic efficiency without a corresponding increase in transpiration.

Water-Quality Requirements for Plants

Salinity is the most serious water-quality problem in agriculture. Excessive salinity can result when the salts that occur naturally in water sources are concentrated by consumptive use of the water and also when salts are removed from saline sediments by streams or aquifers. Evaporation and transpiration are the primary mechanisms for concentrating salts. When water is changed to water vapor, the initial salt load is left behind in a reduced volume of water. To prevent excessive build-up of salts from this process, enough water must be applied periodically to leach some of the salts below the root zone. If this is not done, soil salinity continues to increase until plants no longer can survive. The pick-up of salts by water in sediments below the root zone is of agricultural importance when this water returns to streams and is used again for irrigation. The salinity increases with successive uses.

Beyond a salinity threshold, crop yields decrease approximately linearly with increasing salinity. Threshold values and rates of yield decrease for various crops were tabulated by Maas and Hoffman (1977). Crops differ considerably in response to excessive salinity, and plant parts are not affected equally.
Water-Quality Requirements for Animals

Animals need water to maintain life and support essential physiological processes and growth. Drinking water is as essential for animal performance as is any nutrient. The amount of drinking water needed is affected by the temperature, humidity, water content of the feed, animal function, and the metabolic requirements for water. For mature cows, for example, the needs may range from 6 to 30 gallons per day. Consumption often exceeds minimum requirements (Winchester and Morris, 1956). Dairy cows require approximately 14 gallons of water per day for maintenance, 1 gallon for each 3 pounds of milk produced, and 2 gallons per day for sanitizing the cow. Beef cows also require about 14 gallons per day for maintenance. Factors such as species, body size, feed intake, lactation, ambient temperature, type and amount of nutrients and chemical substances ingested, general state of health, stress, and differences among individual animals all influence animal requirements for water.

Water can serve also as a vehicle to carry toxic substances to livestock and wildlife (Shupe et al., 1981). The greatest concern is for chronic effects rather than the more spectacular but less frequent acute toxicologic cases.

Excessive fluoride in geothermal waters used for irrigation is an example of a water-quality factor that has been found to have a significant impact upon animals (Peterson and Shupe, 1976). Forage crops sprinkled with such waters were not adversely affected, but the forage induced lesions in the permanent teeth (dental fluorosis) and bones (osteofluorosis) of the animals that consumed it.

Irrigation

Introduction

The United States has about 10% of the irrigated acreage in the world. Irrigated land in the United States increased from 21 million acres in 1944 to 51 million acres in 1978, according to the Census of Agriculture (Table 5). About 85% of the irrigated land is located in the 17 western states. The proportion of the total value of crops and forest products that was sold from irrigated farms according to the 1974 Census of Agriculture (U.S. Department of Commerce, 1977) was more than 90% in Arizona, California, Nevada, and New Mexico; 80 to 90% in Idaho, Utah, and Wyoming; and 60 to 80% in Colorado, Nebraska, Oregon, Texas, and Washington. Large increases in irrigation have occurred in the southeastern United States in recent years.

Irrigation is a more costly way to supply crops with water than is precipitation. Nonetheless, production from irrigated agriculture is less variable than that from rainfed agriculture, and irrigation thus contributes to the stability of the U.S. food supply.

Irrigated cropland harvested amounted to 14% of the total acreage harvested in 1978 in the United States, but the value of crop and livestock marketings from the irrigated land in 1978 may be estimated at $26 billion or 24% of the value of the marketings from all cropland and rangeland in the United States in the same year (U.S. Department of Commerce, 1981). Also in 1978, 28% of the persons supplied with food from U.S. agriculture were in other countries (U.S. Department of Agriculture, 1980a), and U.S. exports of agricultural products amounted to $32 billion (U.S. Department of Agriculture, 1980b). Hence, the value of the production from irrigated land considerably exceeds the production from an equal area of nonirrigated land, and it approaches the value of all agricultural exports. The value of agricultural exports has been emphasized in recent years because exports now contribute so significantly to the U.S. balance of trade. In 1978, agricultural exports amounted to 19% of the total exports (U.S. Department of Agriculture, 1980b).

A permanent overhead sprinkler irrigation system in a citrus grove near Avon Park, Florida. Florida is in a high-rainfall region, but many of the soils have a low water-holding capacity, and irrigation is profitable for the high-value crops produced there. In 1978, 72% of the harvested cropland in Florida was irrigated. Photograph courtesy of the Soil Conservation Service, U.S. Department of Agriculture.
Table 5. Irrigation Development in the Top 20 States (U.S. Department of Commerce, 1981 and earlier years)

<table>
<thead>
<tr>
<th>State</th>
<th>Thousands of Irrigated Acres in Indicated Year</th>
<th>Top 20 States, 1978 Acreage Ranking</th>
<th>Irrigated Acres in 1978 as Percentage of Total Harvested Cropland</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1944</td>
<td>1954</td>
<td>1964</td>
</tr>
<tr>
<td>California</td>
<td>4,952</td>
<td>7,048</td>
<td>7,599</td>
</tr>
<tr>
<td>Texas</td>
<td>1,320</td>
<td>4,707</td>
<td>6,385</td>
</tr>
<tr>
<td>Nebraska</td>
<td>632</td>
<td>1,171</td>
<td>2,169</td>
</tr>
<tr>
<td>Idaho</td>
<td>2,026</td>
<td>2,325</td>
<td>2,802</td>
</tr>
<tr>
<td>Colorado</td>
<td>2,699</td>
<td>2,263</td>
<td>2,690</td>
</tr>
<tr>
<td>Kansas</td>
<td>96</td>
<td>332</td>
<td>1,004</td>
</tr>
<tr>
<td>Montana</td>
<td>1,555</td>
<td>1,891</td>
<td>1,893</td>
</tr>
<tr>
<td>Florida</td>
<td>222</td>
<td>428</td>
<td>1,210</td>
</tr>
<tr>
<td>Oregon</td>
<td>1,129</td>
<td>1,490</td>
<td>1,608</td>
</tr>
<tr>
<td>Arkansas</td>
<td>289</td>
<td>858</td>
<td>974</td>
</tr>
<tr>
<td>Wyoming</td>
<td>1,354</td>
<td>1,263</td>
<td>1,571</td>
</tr>
<tr>
<td>Washington</td>
<td>520</td>
<td>778</td>
<td>1,150</td>
</tr>
<tr>
<td>Arizona</td>
<td>736</td>
<td>1,177</td>
<td>1,125</td>
</tr>
<tr>
<td>Utah</td>
<td>1,124</td>
<td>1,073</td>
<td>1,092</td>
</tr>
<tr>
<td>New Mexico</td>
<td>535</td>
<td>650</td>
<td>813</td>
</tr>
<tr>
<td>Nevada</td>
<td>674</td>
<td>567</td>
<td>825</td>
</tr>
<tr>
<td>Louisiana</td>
<td>536</td>
<td>708</td>
<td>581</td>
</tr>
<tr>
<td>Oklahoma</td>
<td>2</td>
<td>108</td>
<td>302</td>
</tr>
<tr>
<td>South Dakota</td>
<td>53</td>
<td>90</td>
<td>130</td>
</tr>
<tr>
<td>Mississippi</td>
<td>3</td>
<td>132</td>
<td>123</td>
</tr>
<tr>
<td>All other states</td>
<td>85</td>
<td>493</td>
<td>1,003</td>
</tr>
<tr>
<td>Total 30 states</td>
<td>20,539</td>
<td>29,552</td>
<td>37,049</td>
</tr>
</tbody>
</table>

Less than 500 acres.

Storage and Delivery

Storage and delivery facilities and operations are the link between surface water sources and the farm. In the West, reservoirs may store water for as much as 2 or 3 years for use during periods of low rainfall. The reservoirs generally provide additional benefits, such as flood control, recreation, and wildlife uses. In the East, much of the surface water used for irrigation is drawn from rivers, streams, and ditches.

Ideally, a storage and delivery system should allow the irrigator to obtain water "on demand," i.e., when needed by the crops. Many delivery systems operate on a demand basis during the off-peak use periods, but are forced to change to a rotation system during peak use periods because canal capacities are inadequate to meet total crop needs. The rotation system can result in plant stress and reduced yields.

On-Farm Irrigation Systems

An on-farm irrigation system includes distribution and application facilities. Distribution facilities include open channels and pipelines. Application facilities include those for surface, sprinkler, and drip irrigation.

Distribution Facilities

An open channel (ditch) is the most commonly used method of on-farm distribution. Lined channels reduce seepage, weed growth, and irrigation labor requirements. Concrete is the most common ditch lining material. The elevation of ditches is above the field so that water can be directed into the field by opening gates or with siphon tubes. Ditches or pipelines can be used for water which is pumped from wells for distribution.

A portion of Shadow Mountain Reservoir, high in the Rocky Mountains of Colorado. This reservoir is a part of the Big Thompson Project, in which water is diverted across the Continental Divide from west to east. Many reservoirs are scenic and are used for recreational purposes in addition to supplying water for agricultural, municipal, and industrial uses. Photograph courtesy of Charles A. Black, CAST.
A 75-acre irrigation reservoir for muck soils near Celeryville, Ohio. The reservoir is above the level of the surrounding land, and the water flows by gravity through open channels, irrigation pipelines, and water-level control structures to surrounding farms. The reservoir is filled from a nearby stream by pumps that operate automatically during storm runoff periods. Photograph courtesy of the Soil Conservation Service, U.S. Department of Agriculture.

**Application Methods**

The oldest method of application is surface irrigation. Sprinkler irrigation expanded rapidly after World War II. Drip irrigation has evolved during the past 15 years.

With surface irrigation, the field itself is used to convey water through the area being irrigated. The energy to cause overland flow is provided by the slope of the field and by water level differences between the distribution facility and the field. Flow direction may be controlled with furrows or dikes of various sizes and shapes. Common practice with furrow irrigation is to plant row crops on the higher areas or "beds" between the furrows. Water moves through the furrows and soaks into the beds.

In surface irrigation, overland flow and infiltration into the soil occur simultaneously. Uniform distribution of water is difficult to achieve on sloping land because of the number and variability of factors which affect infiltration and surface flow. Runoff recovery systems may be used to recover runoff from sloping land systems for reuse in irrigation.

Sprinkler irrigation systems provide more control over distribution of irrigation water than does surface irrigation. Final delivery from sprinkler systems is made through the air from nozzles. Sprinklers are particularly adapted to steep terrain, sandy soils, and low water supplies.

There are various kinds of sprinkler systems, including permanent, solid-set, mechanical-move, and hand-move. The center-pivot, a type of mechanical-move sprinkler, deserves particular note because of its rapid adoption in recent years. The first center-pivot system was built in 1949 by Frank Zybach of Strasburg, Colorado (Axthelm and Splinter, 1978). A pipeline, normally about 1,300 feet in length, is fitted with nozzles and suspended 8 to 10 feet above the ground on movable towers spaced 100 to 185 feet apart. The pipeline rotates about the center pivot, through which the water is supplied at pressures ranging from 10 to more than 80 pounds per square inch. The motive power can be electric, hydraulic, or water pressure. Although the energy requirement is increased, the low labor requirement has been the chief attraction of center-pivot systems. More than 60% of the sprinkler-irrigated lands in the central and southern Great Plains and the Cornbelt are irrigated with center-pivot systems.

With drip irrigation, a network of plastic pipes is extended throughout the area to be irrigated. Water is delivered to individual plants or groups of plants through perforated tubing on the surface of the soil or
Surface-irrigating cotton near Fabens, Texas. Two-inch tubes are used to siphon the water from the concrete-lined irrigation ditch into the furrows. The level of water in the ditch is above the level of the field, and the field slopes slightly away from the ditch, causing the water to flow by gravity across the field in the furrows between the rows. Photograph courtesy of the Soil Conservation Service, U.S. Department of Agriculture.

Surface-irrigating a field in Washington State. In this field, the water is supplied through a permanently located underground pipe with outlets that lead to the surface every few yards. The outlet in the center foreground supplies water to four furrows. Photograph courtesy of the Soil Conservation Service, U.S. Department of Agriculture.

Surface-irrigating corn in Nebraska. Here the water is delivered to the field in a pipe laid on the surface of the soil. The pipe has "gates" or openings from which the water is discharged into the furrows between the corn rows. Open ditches can be laid across level or slightly sloping land, but pipes can be used on land with a more irregular surface. The pipes are relatively light and can be moved from one place to another. Photograph courtesy of the Soil Conservation Service, U.S. Department of Agriculture.

sometimes underground. The flow rate is so low that the water drips onto the soil and is absorbed with little or no ponding on the surface. Low discharge rates require small outlets, which are subject to plugging by sediment, chemical precipitates or biological growth. The equipment thus must be inspected frequently to detect and correct malfunctions.

**Water Management**

Development of new irrigation equipment and management technology since the 1940s has enabled farmers to improve irrigation efficiency. For example, concrete-lined ditches, siphon tubes, and gated aluminum pipes have enabled more uniform and efficient irrigation with less labor.

Water management in irrigation is somewhat different in humid and subhumid regions than it is in arid and semiarid areas, where irrigation is a necessity to produce many crops. In arid and semiarid areas, most of the soils irrigated have a relatively large water-holding capacity. The objective in irrigation is to fill the soil reservoir with water, supplying only such excess amounts of water as may be needed to prevent undue buildup of salinity. In humid and subhumid regions, most of the soils irrigated have a relatively low water-holding capacity, and irrigation is needed if there is a water deficit in the range of an inch or more. In these areas, the objective in irrigation is usually to fill the soil
reservoir with water but to avoid an excess because of the loss of nitrogen fertilizer and water this would entail. Only rarely is salinity a problem. If the soils irrigated in humid regions have slow drainage, rainfall following irrigation may have adverse effects on crops.

**Water Management Performance**

During the past three-quarters of a century, irrigation scientists and engineers have worked with farmers to improve irrigation technology and crop production per unit of water consumed. Performance criteria have been developed to describe the relative effectiveness of irrigation water used in agriculture and the ability of irrigation systems to distribute water uniformly over the fields. Some of these criteria are:

*Irrigation efficiency.* Ratio of water consumed by the crops to the water withdrawn from the source (defined by O. W. Israelsen in 1932).

*Water-Use efficiency.* The quantity of the marketable or usable portion of a crop produced per unit of water used in evapotranspiration (evaluated for many crops under field condition and varying amounts of inputs of other resources such as fertilizer during the 1950 to 1975 period).

*System performance.* Irrigation system performance as evaluated by several criteria such as water-application efficiency, uniformity coefficient, and a number of other similar engineering terms used in planning, designing, and evaluating irrigation systems.

Irrigation efficiency is the most widely used criterion, but it often is used interchangeably with other terms and is interpreted in different ways. Planners and designers use this term to determine the water supply needed and the storage volume and capacity of the water-distribution system, whereas farmers and technical service groups use the term to evaluate how well irrigation systems are being used.
Augmentation of Water Supply

Weather Modification

Cloud seeding is a way of augmenting the water supply by increasing the natural precipitation. This process was discovered more than 30 years ago, and it since has been subjected to intensive research and development. Generally, the average increase of precipitation through use of existing cloud-seeding techniques is believed to be less than 20%. There is evidence of decreases in rainfall in some instances (Bark, 1977). The uncertainty about the results that may be achieved leads to the conclusion that cloud seeding as a technology is not ready for general use. Further experimental and developmental efforts are required, according to the Weather Modification Advisory Board (1978). Nonetheless, more than 7% of the United States was subjected to cloud seeding in 1977, and several states have enacted laws to regulate the practice.

Procedures have been developed also to increase the snowfall that results during the winter when air masses rise as they pass over the mountains in the West, and thus to increase the amount of water subsequently available for irrigation. In February 1977, a winter program of cloud seeding to increase the snowfall in the mountains was carried out by the state of Colorado in response to water deficiencies resulting from the severe drought of 1976. The program was continued the following year, but because of heavy snowfall in December 1977 and January 1978 the program was discontinued in mid-February 1978. In California, seeding of winter storms in the mountains has been practiced by hydroelectric companies for the past three decades. For the past decade, the state of Utah has had a weather modification program which deals primarily with increasing the snowfall in the mountains. The probability of an increase in precipitation as a result of seeding winter storms in the mountains is greater than that associated with seeding summer thunderstorms (Sax et al., 1975).
Desalination of Brackish Water

Water desalination has increased rapidly in the last 25 years, but the supply of fresh water in the United States from desalination is still less than 0.002% of the water from rainfall. The process provides only a small proportion of the supply needed by agriculture. With increased energy prices, costs are now so great that desalination is not expected to contribute substantially to agricultural water supplies.

Water Reuse

Treated water from industrial plants, electrical generation facilities, and municipal sewage disposal operations can be reused in irrigation. Although the feasibility of water reuse depends upon the cost of treating the water for recycling, reuse is expected to account for an increasing portion of the supply of water to agriculture in the future. Water from irrigation return flows and municipal sources is used widely at present.

Vegetation Manipulation

Augmentation of water supply through manipulation of the vegetative cover is possible also (Hibbert, 1979; Horton, 1976; Horton and Campbell, 1974). Management practices which can be employed to affect available water supplies include:

- **Removal of woody plants.** Streamflow in forested watersheds can be increased by reducing evapotranspiration losses. Removal of vegetation which has a high transpiration rate may reduce on-site consumptive use of water. In arid and semiarid watersheds, however, converting the vegetation from shrubs to grass is not likely to increase streamflow. Rangeland manipulations only rarely result in appreciable increases in water for downstream or industrial purposes.

- **Removal of phreatophytes.** In some cases, removal or treatment of phreatophytes (water-loving vegetation) along waterways can result in lower transpiration losses of water (Davenport et al., 1979). Removal of salt cedar along waterways in the Southwest frequently has resulted in increased streamflow. Studies in other areas have failed to demonstrate similar results.

- **Landscape manipulation.** Water supply can be increased by changing the contours of the landscape to modify the surface runoff characteristics. In the United States, most of this manipulation in the arid regions is done to develop land for uses other than agriculture. It is possible to change the runoff patterns in such a way that water is concentrated locally in depressions. Plant growth is enhanced in areas of concentration. These practices were a part of the land management of ancient agricultural systems which are being tested again in Israel.

Conservation of Existing Supplies

Conservation is used to extend the use of water for crops and animal production as well as human needs. Humans have been involved continually in water conservation. The methods have ranged from conservation tillage to techniques such as water harvest and diversion.

Conserving water also may reduce the quantity of energy required in agricultural uses to move the water to a field for irrigation. Studies in California (Davenport et al., 1977) and Nebraska (Gilley and Watts, 1977) indicate that the equivalent of about 40 to 50 billion kilowatt hours of electrical energy could be saved each year by implementing specified conservation practices in irrigation. To achieve this saving would require increasing irrigation pumping plant efficiency, improving scheduling of irrigation, reducing water application according to field-determined needs, reusing irrigation runoff water, and improving irrigation system design. Other benefits of water conservation include decreased leaching of nutrients, increased yields and crop quality, and decreased pollution of receiving waters.

In subhumid regions, conservation practices involve both the removal of excess water without excessive soil erosion and the retention of adequate quantities of water in the soil and in surface impoundments for use during periods of deficient rainfall. Conservation in semiarid regions centers around storing the precipitation in the soil and using the conserved water effectively. About 14% of the cropland in the 17 western states is devoted to summer fallow (U.S. Department of Commerce, 1981), wherein cropping is attempted in alternate summers and the intervening period is devoted to storing water in the soil for the next crop. Typically, summer fallow results in storage of about 16% of the total rainfall received in the fallow period in the Great Plains, and the storage efficiency decreases from north to south. In some areas, conservation efforts extend to snow management on fields and watersheds.

The efficiency of water use in irrigation can be increased in a number of ways which are reviewed briefly in the following paragraphs:

- **Reducing losses from the storage and distribution system.** The objectives here are to reduce seepage, leakage, and spillage.

- **Improving the irrigation management system.** The objectives here are to irrigate when needed, but to avoid
runoff and to avoid losses of water to deep percolation to the extent consistent with salinity management. The reductions in losses described in this and the preceding paragraph, however, will not reduce the net, basin-wide water demand.

**Reducing evaporation.** Means of reducing the loss of water by evaporation include reducing irrigation frequency, reducing the area of wetted soil surface, creating a dust mulch, keeping crop residues on the surface of the soil, using a chemical or plastic mulch, planting into small grain stubble, intercropping or relay cropping, using pregerminated seeds, and lowering high water tables by installing drains or using crops which can lower the water table. Estimates of the potential reduction in evaporation from use of these techniques range from 2 to 25% of the total evapotranspiration.

**Reducing transpiration.** Measures that reduce transpiration with a minimum reduction in yield include:

1. Removing water-loving vegetation from stream banks, supply ditches, drains, and fields (these measures can affect the wildlife habitat adversely).
2. Shifting to shorter-season varieties or other varieties with lower transpiration than the current variety, shifting the planting date, and harvesting as soon as feasible.
3. Optimizing crop density, canopy roughness, row spacing, and row direction.
4. Substituting a crop that grows during a season of lower transpiration than the current crop.
5. Substituting a crop capable of producing an

Mulches reduce evaporation of water from the soil and control weeds. **A.** A mulch of black polyethylene used with tomato plants. **B.** A mulch of straw used with grapes. Photograph A courtesy of the U.S. Department of Agriculture and B courtesy of Charles L. Benn, Iowa State University.
acceptable yield under water stress. (6) Controlling the environment.

Measures that reduce both transpiration and yield include: (1) Applying reflectants or transpiration retardants to unstressed leaves. (2) Allowing water stress to develop in the plants under deficient irrigation. Measures for reducing evaporation and transpiration generally provide the principal opportunities for increasing the efficiency of water use in irrigation (Davenport and Hagan, 1979). In this connection, one may argue with some justification that the greatest increases in efficiency of water use in crop production may be achieved by producing crops in areas in which transpiration is relatively low, i.e., the humid regions. And, because irrigation often produces increases in crop production in the humid regions, greater emphasis on irrigation research and development in these regions would be appropriate. More water is available for irrigation in humid regions than in arid regions, and this water usually lies close to the surface, does not salinize the soils, and is not subject to exhaustion because of rapid recharge. The Coastal Plain of the Southeast is perhaps the outstanding example.

Increasing plant productivity per unit of water by avoiding other constraints on production. Constraints on production that may be overcome to some degree with a resulting increase in plant productivity per unit of water used in irrigation include restricting agriculture to the most productive land, selecting the best adapted crop variety, selecting the optimum time for planting and harvest, utilizing optimum fertilizer practices and pest-control measures, providing needed leaching of excess salt, and providing adequate surface and subsurface drainage.

Decreasing the waste of plant material produced. The loss of plant material that has been produced at the expense of consumptive use of water in evapotranspiration may be reduced by adopting adequate frost-control measures and changing from those that use water to other methods; providing supplemental irrigation to permit acceptable yields and efficient use of limited rainfall; providing adequate disease and insect control; avoiding labor, transport, and processing problems at the time of harvest of perishable crops; and providing adequate stock water to allow livestock to harvest range forage effectively.

The Institutional System

Institutional development in irrigation includes the organizations and management systems, the laws and regulations, and the structure and function of government related to irrigation. Society has developed a set of institutions and systems to manage and direct the use of water for irrigation. These institutions and systems are based upon several factors, including social values or beliefs of what should or should not be done and how it should be done.

Organization and Management Institutions

Numerous organizational structures have become institutionalized to provide for the delivery of water in the United States. The Census of Agriculture lists seven general categories of organizations that deliver water to farmers. They are: unincorporated mutual companies, incorporated mutual companies, irrigation and other types of districts, Bureau of Reclamation, Bureau of Indian Affairs, state and local governments, and commercial and other.

Laws and Regulation Institutions in Water Rights

In surface water law, there are two approaches to water capture and use. The first is the "riparian doctrine" patterned after English legal tradition, according to which the owner of private land along a stream owned the stream and had a right to have the stream continue to flow in its natural condition by or upon that land. The owner could make use of the water so long as the stream remained undiminished in quantity and quality when it left his land. In the United States, this doctrine has been modified by a "reasonable use" concept, but this concept is limited to not unreasonably interfering with the rights of other riparians or adjacent owners. Owners of nonriparian lands may, under certain conditions, make reasonable use of any remaining waters. The reasonable-use requirement limits the use to the quantity reasonably required for a beneficial use and prohibits waste. This doctrine is utilized chiefly in the eastern states and in some parts of California.

The second doctrine is "prior appropriation," which permits a water right to be acquired by diverting water from a water course for a beneficial use. The water right also carries a priority date, which was established under the principle of "first in time, first in right." The first person to appropriate water and put it to reasonable and beneficial use has a right superior to any later appropriators. This right is a real property right and can be sold or bequeathed, although most states require administrative approval to change the point of water diversion. In the western states, water laws generally are based upon the doctrine of prior appropriation.

Some eastern states have established a permit system for managing their water resources, and others are considering it. The permit system is essentially a modified appropriation doctrine.
Groundwater Doctrine

One of the difficult problems with irrigation has been the control of groundwater utilization. Various states have adopted one or more of four different doctrines for groundwater utilization: (1) Absolute ownership of water under the land. (2) Reasonable use, which recognizes the right of all to the resource. (3) Correlative rights, in which the landowner must correlate his use with others. (4) Doctrine of prior appropriation, in which the resource is the property of the state and is subject to appropriation.

In 1980, Arizona adopted groundwater legislation which allows the state to limit pumping in designated areas. The question of resource ownership was not addressed directly, but the state was given authority to control the use of groundwater.

Federal Government

Federal government agencies have been involved in irrigated agriculture through Congressional acts such as the Desert Land Act of 1877, the Carey Act of 1894, and the Reclamation Act of 1902. In 1976, the projects of the Bureau of Reclamation were delivering the total water supply to 14% of the irrigated lands in 17 western states and a supplemental supply to about 11%. Some 35 federal programs in 10 separate agencies are providing some type of assistance to irrigation. Almost $175 million are spent annually by these agencies in addition to the $550 million spent by the Bureau of Reclamation and Bureau of Indian Affairs on construction programs. Costs of water to water users nominally include costs of construction if farmers have the ability to pay these costs. Historically, however, interest costs on Bureau of Reclamation projects have been low or forgiven. These costs represent the largest single component of the cost of constructing irrigation projects.

Federal programs include planning, technical assistance, research, education and demonstration, cost-sharing, grants, loans, regulations, and acquisition of land and water for environmental purposes. Nearly all of these programs are carried out cooperatively with state, local, and private agencies.

State and Local Governments

State and local government programs have been stimulated by federal programs, and most states have an impressive array of agencies that relates to water resources. Private water rights are regulated at the state level.

Local agencies consist of water districts and conservancy districts which are established to perform a service, usually that of supplying water for various uses. They have power to levy taxes on designated areas to develop delivery systems.

Considerations in Allocating Water

Water is required in production and consumption activities of various kinds. The value of some uses of water, such as those for agriculture, manufacturing, retailing, and transportation, can be quantified in economic terms, but quantification of economic values in use of water for ecological, scenic, domestic (household), and certain other uses is more difficult.

Historically, priority of need has been a consideration in allocating water to alternative users. Some federal water has been delivered at prices below costs to encourage users to react in specific ways such as development of irrigation. To provide minimal amounts of water required to fulfill human requirements, allocation procedures for water have been developed through political actions.

Economic Competition and the Demand for Water

The statutes establishing the legal basis for water-rights law in the West were enacted when water supplies were relatively plentiful compared with demand. It was recognized that agricultural production of crops required water applications through irrigation. For irrigation development to occur, rights to utilize water were granted to prospective users to give them the security of continued use to induce investment for stability and profitability.

Continued development of the West resulted in increased demand for water. In response to increased demand, private and public investment was used to augment water supplies. In general, the lower-cost water-collection and storage sites were developed first, which meant that, over time, new supplies and sites had increased developmental costs. As water became increasingly scarce and valuable, institutions were developed for specific purposes.

The emergence of water scarcity can be described for cases in groundwater as well as stream flows. The Ogallala aquifer in six of the Great Plains states is an example of a finite groundwater supply which has an overdraft of water. Economic exhaustion of the formation is occurring throughout the area.

Estimates of streamflow, consumptive use, and optimal instream flow indicate shortages in some basins in the near future (Table 6). The estimates in the table do not include seasonal variations for droughts, and they do not show locational demands.

Disputes regarding mechanisms to allocate water have

<table>
<thead>
<tr>
<th>Water Resource Region</th>
<th>Total Stream Flow</th>
<th>Total Consumptive Use</th>
<th>Remaining Stream Flow</th>
<th>Optimal Stream Flow (1975)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Souris-Red-Rainy Rivers</td>
<td>7.6</td>
<td>0.5</td>
<td>7.1</td>
<td>4.1</td>
</tr>
<tr>
<td>Missouri River</td>
<td>68.9</td>
<td>28.6</td>
<td>40.1</td>
<td>38.0</td>
</tr>
<tr>
<td>Arkansas-White-Red Rivers</td>
<td>76.0</td>
<td>13.4</td>
<td>62.6</td>
<td>25.7</td>
</tr>
<tr>
<td>Texas-Gulf</td>
<td>39.9</td>
<td>14.0</td>
<td>25.9</td>
<td>25.7</td>
</tr>
<tr>
<td>Rio Grande River</td>
<td>6.2</td>
<td>5.4</td>
<td>0.8</td>
<td>2.6</td>
</tr>
<tr>
<td>Upper Colorado River</td>
<td>15.6</td>
<td>5.6</td>
<td>10.0</td>
<td>8.9</td>
</tr>
<tr>
<td>Lower Colorado River</td>
<td>9.3</td>
<td>11.0</td>
<td>-1.7</td>
<td>7.7</td>
</tr>
<tr>
<td>Great Basin</td>
<td>7.0</td>
<td>4.9</td>
<td>2.1</td>
<td>3.8</td>
</tr>
<tr>
<td>Pacific Northwest</td>
<td>300.8</td>
<td>19.4</td>
<td>281.4</td>
<td>239.6</td>
</tr>
<tr>
<td>California</td>
<td>80.6</td>
<td>34.0</td>
<td>46.6</td>
<td>36.5</td>
</tr>
</tbody>
</table>

*U.S. Fish and Wildlife Service estimates for optimal fish and wildlife habitat conditions.

taken decades to resolve. A resolution thought to be final may be subject to subsequent rehearing and reinterpretation, with the result that allocative disputes may never be settled entirely. The atmosphere of uncertainty that is created may discourage allocation of water to its highest valued use. (When referring to highest valued use, the highest economic value is not necessarily implied. Noneconomic values not susceptible to quantification may well be included in a summation of judgment as to which use has the highest value.)

For the most part, institutional barriers have inhibited transfers of water. As applied in most states, both riparian and appropriation doctrines prohibit transfers that injure third parties. Where no restrictions on pumping exist, managing aquifers presents some especially serious challenges.

The water saved by conservation investment often cannot be utilized by the conserver, and it cannot always be sold. In some states, a portion of a water right may be forfeited as a result of nonuse stemming from conservation practices. In such instances, benefits accomplished by conservation may accrue primarily to other water users, and water conservation is not practiced as intensively as might otherwise be expected.

In addition to legal arrangements for allocating scarce water supplies, numerous temporary arrangements for rationing water have been developed. During droughts, water purveyors often reduce deliveries to users by some proportionate amount. Municipalities may enact temporary ordinances restricting or prohibiting the use of water for certain purposes such as yard watering and car washing. Such rationing schemes have worked surprisingly well in the immediate short run where users are willing to accept the critical but temporary nature of the situation. Moral appeals to save water have had some short-term effects during severe water shortages. However, these arrangements involving voluntary compliance tend to work poorly, if at all, in the long run since incentives are lacking.

A well-functioning market system results in scarce resources being obtained by those willing to pay the highest price for them. In this way, scarce resources find their way to the uses with highest economic value, and the resources are said to be allocated in an economically efficient fashion, that is, in a way that maximizes their economic value. One notable feature about the allocation of water by the current set of legal and institutional and other mechanisms is the relative absence of market allocation systems.

Current practices in the pricing of agricultural water result in its misallocation in economic terms. During the early history of water development in the West, special emphasis was placed upon the need to settle the area, preferably with family-sized farms. This emphasis was manifested in federal projects in which some agricultural water users were not required to pay the total costs of developing and conveying water for irrigation purposes; prices were established according to estimates of ability to pay.

As the competition for water intensifies, more attention will need to be devoted to devising new mechanisms for allocating water among competing uses to replace or modify existing mechanisms that were responsive in a past era. Results of studies suggest that the current environment requires mechanisms which facilitate the transfer or reallocation of water among competing uses. The fundamental change required to facilitate transfer or reallocation is a system of laws or rules allowing for voluntary exchange of water rights while protecting the interests of third parties.

A commonly expressed argument against relaxing the institutional barriers is that a market for water rights would severely reduce the amount of water available for agriculture. This fear arises from the belief that uses with higher economic value would bid sizable amounts of water from agriculture, with the result that insufficient quantities would remain for the production of food and fiber. A recent study of water use in California by Erlenkotter et al. (1979), however, suggests that less than 20% of the water used by agriculture
would be transferred to other uses. The study shows also that agricultural water users who choose to sell their rights to other sectors would receive a price substantially higher than they would expect to receive if they used the water for irrigation.

In disputes over the allocation of resources, it is often argued that society has many goals, some of which are not consistent with the maximization of economic values in resource use. Indeed, most political decisions involve options or choices to pursue certain objectives at the expense of maximizing economic value. Often ignored in the decision-making is the magnitude of economic value foregone in choosing to favor a noneconomic goal.

The limited experience available regarding the use of market-like mechanisms for transferring water suggests that they work well. Evidence from Delta, Utah (Gardner and Fullerton, 1968) and the Big Thompson project in Colorado suggests that water does, indeed, find its way to uses with higher economic value if those who sell their water do so voluntarily. This evidence shows that where such transfer mechanisms have been used, some individuals have been made better off, while virtually none have been hurt.

Interbasin transfer of water is occurring currently in the United States in both arid and subhumid regions. The most significant reallocations are in California, Colorado, and New York. Additional proposals are under serious review, including diversions from the Colorado, Snake, and Columbia Rivers in the West. The Texas Water Plan would divert 17 MAF of water from the Missouri and Mississippi Basins as far west as New Mexico. Recently, South Dakota announced plans to sell water to the coal industry for transporting coal as a slurry through pipelines from the western coal fields.

The transfer of water from one basin to another has political and social implications as well as economic impacts. Thus, the National Water Commission (1973) noted that, “In the final analysis, it is Congress which must exercise decision making responsibilities with respect to interbasin transfers. The economic criteria which the Commission advances cannot and should not be binding on Congress.”

Social Impacts

Empirical evidence documenting the social impacts of increased water use in irrigation is sparse. Effects on farm size and local communities undoubtedly are contingent upon the economic arrangements made for increased use, access costs, and effect upon market prices for goods produced. Irrigation in relatively dry regions generally affects local agriculture dramatically, changing land-use patterns, valuation, and ownership. Because of the increased intensity of cropping, management and capital requirements generally are greatly increased, and the entry of individuals into farming is impeded. Benefits flow from a more productive and stable agriculture in an area and from greater availability of food and fiber to consumers. It is not always clear, however, when, where, and how the social costs and benefits are distributed. Some relationship probably exists between the magnitude of the impact that increased water use has upon the structure of agriculture in an area and the extent of effects upon the local community and surrounding population.

Public reaction to subsidized water-use arrangements often is most intense when a small or limited group of individuals is perceived as receiving excess benefits. Little recognition generally is given, however, to the broader distribution of small benefits to consumers who pay lower prices due to increased supply or to the high level of private investment that generally accompanies the subsidy by the general public.

Changes in agricultural water use will be subjected to increasingly intensive scrutiny in the future as regards both the right to increase use and the effect that use may have on other groups. Shifts in water use that affect other regions will be open to increasing public discussion. Government decisions to assist or regulate agricultural water use will increasingly incorporate social costs as a factor. Social goals and private profit in agriculture are not incompatible, although subsidies to water use undoubtedly will receive greater attention for their effects on people. Agriculture will have to expend more effort to justify its claims to water, particularly under scarcity conditions, and will have greater responsibility for the environmental impacts of the water it uses and returns to the system. Although current overproduction may be temporary, policy makers increasingly will be aware of, and concerned about, the paradox of governmental programs which tend to subsidize increased production while other programs are designed to discourage production. In general, the agricultural industry will be held more closely accountable for the way it uses water and the effect that use has on individuals and communities.
Some Policy Issues

Listed in the following paragraphs are some policy issues that have to do with use of water in agriculture. Most are matters of long-standing concern that have not been resolved and, if addressed in the future, probably would benefit from continuing adjustments with time as agriculture and water problems evolve. The order in which the issues are listed is not intended to imply an order of significance.

Water Conservation

Although water conservation by individual agricultural users does not necessarily imply more water for other users or reduced depletion of groundwater supplies, it does imply more productivity per unit of water used. Continued research and education to point the way to greater economic efficiency through adoption of appropriate water conservation techniques will result in improvements in practice. A problem exists in some areas, however, where the policies in effect fail to provide the incentives needed to encourage conservation practices. For example, laws in some states would allocate the water saved to other users. Where groundwater is concerned, a saving by one user may be appropriated by an adjacent nonsaver who pumps the water for his own use.

Water Quality

The principal pollutant of water in the United States is sediment, much of which has been eroded from agricultural land. Excessive erosion degrades the quality of both soil and water. The problem in reducing soil erosion and the associated degradation of water quality is that the needed conservation practices are not profitable enough in the short run to persuade producers to adopt the practices. The long-term importance of erosion control is not yet sufficiently appreciated to result in the policy decisions required to encourage farmers to adopt the needed practices.

For its direct and immediate impact upon agriculture in the West, salinity of irrigation water is of first importance where water quality is concerned. Excessive...
salinity in the water inhibits plant growth and, in extreme instances, prevents it. The salts in irrigation water become increasingly concentrated in the soil as the plants use the water, and these salts must remain in the soil, be leached downward into the groundwater, or be removed in drainage canals. Most of the water in drainage canals in areas with salinity problems is derived from salty groundwater that has seeped into the canals from the adjacent areas. In the past, the standard agricultural practice was to protect the quality of the soil as a medium for plant growth by using amounts of low-salt irrigation water sufficient to keep the excess salts flushed out of the soil and to carry these salts away in the drainage water.

The policy decision to protect the quality of surface water by reducing the allowable discharge of salts into drainage canals assures the buildup of salts in the groundwater and the soil, and it increases the hazard of crop yield limitations due to excessive soil salinity. The effects of this policy decision are compounded by the currently increasing cost and decreasing availability of high-quality, low-salt water. These circumstances are forcing agriculture to use water with an increasingly high concentration of salts and to increase the efficiency of water use, both of which increase the concentration of salts in the water in the soil and in the groundwater.

Groundwater Depletion

Large volumes of groundwater are being used by agriculture, industry, and municipalities, and declining groundwater levels and soil subsidence are occurring in some areas. Initially, concerns were expressed for the western states, but similar situations are found in other areas in the United States. For the future, to what extent should the overdraft of stored groundwater resources be restricted to prolong their life? And, once the resources are depleted or are no longer economical to use, to what extent should taxpayers at large be obligated to protect the local commitments and investments that have been based upon overestimates of the length of time the resources would last?

Water Rights

The two principal legal doctrines (the riparian doctrine and the doctrine of prior appropriations), under which water rights were established many years ago, now prevent the economically efficient use of water by making it difficult or impossible for the owner of an irrigation water right to transfer the right to potential users whose use of the water may have higher economic value. Should these doctrines be updated to meet the needs of the future? Additionally, undetermined water rights reserved by the federal government are causing uncertainty, controversy, and litigation in several states. Is it possible to clarify these rights?

Interbasin Transfers

Interbasin water transfers currently are occurring in both western and eastern states, and are being considered increasingly as a means of changing water balances in local areas. In principle, interbasin transfers do not differ from other water supply projects. But they often are more expensive and more political. For the future, to what extent should interbasin transfers be rationalized on the economic basis of benefits in receiving areas versus the sum of the costs of (a) curtailment of uses of water in the region of origin and downstream areas and (b) the costs of transfer, and to what extent should the transfers be justified on the basis of noneconomic considerations?

Water Pricing

Currently, water pricing is determined by a large number of boards, organizations, and governmental agencies. Significant differences exist in the price charged for different uses of water from a given source. Such differences in price mean that water, a scarce resource, is not being used in such a way as to maximize its beneficial returns to society. The market mechanism is the most effective means known to encourage water conservation and water use for its most productive purposes. For the future, to what extent should the prices charged for water and water-related services reflect their cost, and to what extent should use restraints be put into effect so that allocation of water use by the market mechanisms will assure that the social benefits will be positive?

The 160-Acre Limitation

One of the issues in water use in the West that has been debated heatedly in recent years is the limitation of federal water use to tracts no larger than 160 acres per individual or 320 acres for a married couple. The limitation was established early in this century to encourage family farms, which at that time were popularly considered to be of a size much smaller than many family farms of today. Federal water often is priced considerably below its market value, and so it is desired by farm operators. Currently, the 160-acre limitation is not being enforced uniformly, and the issue of enforcement is in inactive litigation. Four fundamental positions have been advanced: (1) There should be continued subsidy with acreage limitations. (2) There should be continued subsidy and no acreage limitations. (3) There should be no subsidy, but there should be acreage limitations. (4) There should be no subsidy and no limitations. At the time of this writing in July 1982, a compromise bill had passed the U.S. House of Representatives, and a different compromise bill was ready for floor action in the Senate. Both bills increase the number of acres eligible to receive federal water at
below-cost rates, and both make federal water available at a higher price to irrigate additional land beyond the acreage limits specified for low-cost water.

**Funding of Water Projects**

Some of the large water projects in the United States have been financed and constructed by the federal government. In some instances, the federal government has assumed much of the cost for these water projects. In the future, to what extent should the direct beneficiaries of water projects be required to bear their appropriate share of the development and operating costs?

The current trend in development of water projects is toward increasing the participation by local and state agencies. In some instances, low interest rates have been granted by the federal government to local and state agencies to fund water development projects, a practice that leads to overestimation of the benefit-cost ratio. In the future, to what extent should competitive interest rates be charged for funding such projects?

**Other Government Policies**

Other government policies that seemingly are unrelated to water may affect water use to an important degree. Price support programs, export policies, and land-use policies are examples. In general, policies that affect the level of production will affect water use. Because U.S. agriculture is a complex, competing system involving regions with different resource endowments, the responses of individuals to broad national policies may result in inefficient use and misallocation of resources in certain regions. Producers respond to price signals. Hence, when the government sends signals to producers in the form of a national policy that, for example, artificially increases the price of a certain commodity, producers are induced to allocate resources, including water, to produce that commodity even though it could not otherwise be produced economically in their region. A similar effect results when a national policy causes a production input such as water to be supplied to producers at artificially low prices. Such effects are examples of what, in economic theory, is termed misallocation of resources.

Seeding winter clouds in the mountains of western Colorado. The station shown here has three silver iodide burners mounted on the scaffold to the right of the building. Two are in operation. The silver iodide particles, which average about 2 millionths of an inch in diameter, are borne aloft by the winds and serve as nuclei for the formation of ice crystals in the clouds being seeded. Photograph courtesy of L.O. Grant, Colorado State University.

**Induced Increases in Precipitation**

Advances are being made in increasing winter snowfall in mountainous areas, and some practical use is being made of the techniques of cloud seeding that are employed for that purpose. Whether the extent of the practices and knowledge of the effects currently justify development of policy and regulatory legislation may be debatable, but the potential consequences of widespread usage of techniques to increase precipitation probably are such as to justify eventual consideration, not only because of the differences of views about the desirability of increases in precipitation in the target areas, but also because of possible associated decreases in precipitation in nontarget areas.

**References**


