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Effective Use of Water in Irrigated Agriculture

Council for Agricultural Science and Technology

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CAST provides summary information on scientific aspects of key national issues in agriculture and food processing to the government, news media, and the public. As an educational organization, CAST takes no advocacy stances on issues.

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Cover Photographs
(Left to Right, Top to Bottom)

Laser land leveling. Laser-controlled land leveling enables efficient basin irrigation. Photograph courtesy of Robert C. Bjork, Agricultural Research Service, Beltsville, Maryland.

Alternate furrow irrigation. Alternate furrow irrigation enables applying small amounts of water to young row crops. Photograph courtesy of Robert C. Bjork, Agricultural Research Service, Beltsville, Maryland.

Center pivot irrigator. Center pivot irrigation system enables automatic, efficient irrigation of land not suitable for surface irrigation methods. Photograph courtesy of Michael Deacon, Valmont Industries, Inc., Valley, Nebraska.

Lateral-move irrigator. Lateral-move irrigators can apply water uniformly at low rates and at low pressures. Photograph courtesy of Marvin E. Jensen, Colorado Institute for Irrigation Management, Fort Collins, Colorado.

Trickle irrigation of beans. Trickle irrigation system irrigating a high-value row crop. Photograph courtesy of Richard K. Willis, James Hardie Irrigation, El Cajon, California.

Trickle irrigation of grapes. Trickle irrigation system is well-suited for widely spaced, high-value crops like grapes. Photograph courtesy of Dale Bucks, National Program Staff, Agricultural Research Service, Beltsville, Maryland.

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Preface

Periodic droughts, increasing world population, competing interest in water, water quality, and pumping costs represent some of the major underlying issues behind the CAST Board of Directors' decision to approve a project on "Efficient Use of Water in Irrigated Agriculture."

An ad hoc evaluation committee chaired by previous board member Dr. Parker F. Pratt recommended several possible areas of review by a task force on irrigation, including these:

1. Considering that some irrigation return flows are used or reused, can significant amounts of water be saved by irrigating more efficiently?
2. Can the water saved by irrigating more efficiently be used for urban water supplies?
3. What opportunities or options do farmers have for increasing irrigation efficiency or for reducing the total water applied per acre of irrigated land?
4. How is the quality of the irrigation water related to water use?
5. How does irrigation efficiency impact the quality of irrigation return flows?
6. What are the relationships between soil properties, such as the variability in water intake rates, crop tolerances and cropping sequences related to water duties?

Pratt's recommendation that a task force be appointed was approved by the CAST Board of Directors in July 1986. Nominations and selection of a 19-member task force took place over the next few months. Dr. Marvin E. Jensen, Director, Colorado Institute for Irrigation Management, was selected as chair. Jensen prepared a proposed outline of the subject matter and submitted it to task force members prior to a meeting held in Denver in January 1987. A two-day meeting allowed task force members to reach consensus on the scope of the report. They also decided on writing assignments and established a calendar for writing, reviewing, and publishing the document.

CAST's policy is that task force members not only write but extensively review the report during its preparation. This process is prolonged, but it assures task force members of their preeminent role in determining the scientific content of the report.

This report is being distributed to members of Congress, the U.S. Department of Agriculture, the Environmental Protection Agency, the Food and Drug Administration, the Agency for International Development, Office of Technology Assessment, Office of Management and Budget, media personnel, state legislatures who have asked to receive CAST publications; and to institutional members of CAST. Individual members may receive a copy upon request. The general public may purchase copies at $5.00.

On behalf of CAST, we thank the task force members, especially Dr. Jensen, who gave of their time and talents to prepare this report as a scientific contribution to Congress and the general public. We also thank the employers of the task force members, who made the time of the participants available at no cost to CAST. The members of CAST deserve special recognition because the unrestricted contributions they have made in support of the work of CAST have financed the preparation and publication of this report.

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Abbreviations

AW - Applied water

AWDN - Automated weather data network

CUC - Christiansen's uniformity coefficient

CWSI - Crop water stress index

DP - Deep percolation

E_i - Irrigation efficiency

Ep - Water evaporation from a pan

ET - Evapotranspiration

IRT - Infrared thermometer

LEPA - Low energy precision applicator systems

LR - Leaching requirement

LR_a - Leaching requirement where used with the subscript a denotes available for reuse

LR_u - Leaching requirement where used with the subscript u denotes unavailable for reuse

MAF - Million acre-feet

MFC - Marginal factor cost

MFC_w - Marginal factor cost where subscript w represents water

MVP - Marginal value product

MVP_w - Marginal value product where subscript w represents water

P - Precipitation

Pf - Profit

RO - Runoff

RO_a - Runoff where the subscript a denotes available for reuse

RO_u - Runoff where the subscript u denotes unavailable for reuse

SFV - Surge flow valves

SW - Available soil water

WHC - Water-holding capacity

Summary

Irrigation is practiced where income from increased crop yield and/or quality exceeds the capital investment and annual operating costs associated with irrigation. Irrigation also is practiced to reduce risks associated with nonirrigated farming.

Evidence indicates that some irrigation was practiced nearly 2,000 years ago in the southwestern states, but extensive irrigation has been practiced in the United States for one and a half centuries. In contrast, irrigation has been practiced for 8,000 years along the Nile, for 6,000 years along the Tigris and Euphrates Rivers, and for 4,500 to 5,000 years along the Indus River in the Indian subcontinent and Yellow River in China.

Historically, irrigation stabilized food and fiber production enabling nomadic tribes to settle in communities. More recently, irrigation has played a key role in enabling many developing countries to increase food and fiber production to meet demands from increasing populations. World-wide, irrigated land expanded rapidly after 1950 to about 545 million acres in 1984. The current rate of expansion is less than 1% per year. Similarly, the area of irrigated land in the United States has essentially stabilized because of low commodity prices and limited water supplies.

Increased competition for available water supplies and degradation of water supplies in the United States have created mounting concerns about the use of water in irrigated agriculture. This report summarizes the basic principles of irrigation systems and the basic principles governing irrigation water management. These principles include the factors that affect irrigation decisions, particularly the quantities of water that are applied during irrigations. The report also briefly describes the main irrigation methods and management technology as well as institutions for managing water supply systems and their impacts on irrigation water management. Some recent issues related to irrigated agriculture are summarized and several water conservation concepts are presented. The report concludes with an example water shortage problem and presents several simple alternative approaches to developing the needed water supply by changes in irrigation systems and practices on a hypothetical project.

The purpose of this report is to provide readers with a better understanding of irrigated agriculture, the reasons why growers irrigate, and the factors that affect grower decisions about new irrigation systems and management practices.

Introduction

In the United States, new and expanding water issues are creating increasing demands for alternative and innovative solutions to complex water supply and quality problems. These issues involve: (1) limited water supplies accompanied by increasing water demand and increasing water quality degradation; (2) changing price structure for water; (3) decreasing international agricultural markets along with decreasing national and international market prices for farm commodities; (4) increasing water right transfers and third party effects caused by changes in water uses; and (5) changing institutional systems for managing water resources.

This report characterizes water use in agriculture, particularly irrigated agriculture, and describes alternatives for changing water use strategies and practices, which increase the effectiveness of water use in irrigated agriculture to enable irrigated agriculture to remain competitive with other water users.

1. Overview

Water and Plant Growth

Water is essential for all plant growth. About 85% of green plant material is water. Growing plants absorb carbon dioxide from the air, water from the soil, and energy from the sun to produce carbohydrates — the source of all plant material — through the process of photosynthesis. Carbon dioxide is absorbed by actively growing plants through very small openings in the leaves called stomata. When plants are turgid, the stomata of most plants open during daylight and close at night. Plant cells within the stomatal cavities through which the carbon dioxide is absorbed are wet. When stomata are open, water evaporates from wet cells and diffuses through the stomata to the atmosphere — a process called transpiration. Water that evaporates as plants absorb carbon dioxide cannot be reduced without affecting plant growth.

The rate of transpiration from a well-watered crop that fully covers the soil is determined mainly by the amount of heat energy received from the sun (solar radiation). The transpiration rate also is influenced by atmospheric conditions such as the temperature and dryness of the air and wind speed. Transpiration increases with increasing wind speed, which reduces the resistance to vapor transfer from the plants to the atmosphere. The vapor pressure gradient from wet plant cells to the atmosphere increases as temperature increases and the air becomes drier. Plant characteristics also influence the transpiration rate. These include the amount of solar radiation that is reflected, the stomatal resistance, and the aerodynamic roughness of the crop.

Evaporation from soil and plant surfaces also depends on available energy and resistance to vapor transfer. The combined process of transpiration and evaporation is called evapotranspiration (ET).

In a given climate, the daily rate of ET increases as young plants develop. Plant growth expands the leaf area and transpiration increases. Leaf area and transpiration continue to increase until a full green cover or crop canopy has been established. Then, climate largely controls the ET rate. In most of the United States, common farm crops planted in the spring develop a full crop canopy by late June or early July. The daily rate of ET from a well-watered crop with a full canopy increases from spring to midsummer due to increasing solar radiation and air temperature and decreasing humidity. In July, the ET rate may vary from one-quarter to one-half inch depth over the field per day. The daily ET rate decreases after July and mid-August as solar radiation and air temperature decrease. It decreases more rapidly as crops begin to mature, plant leaves dry, and the rate of photosynthesis decreases.

Assuming a depth of daily ET of one-third inch, the amount of water vaporized in one day from an acre of a well-watered crop, whether irrigated or nonirrigated, is about 1,200 cubic feet or 9,000 gallons. The amount of water evaporated in one day from a 160-acre farm in July may be as high as 1.44 million gallons. Because of these large volumes, larger units of water are used to describe the amount of water used by agriculture or evaporated from lakes and reservoirs. These units are the acre-inch and the acre-foot (12 acre-inches). For example, with a daily ET rate of one-third inch over 160 acres, the daily volume of ET would be 53 acre-inches or 4.4 acre-feet from this area.

The total amount of water required to produce a crop like corn is about 2 acre-feet per acre, or 320 acre-feet for a 160 acre farm planted to corn, whether irrigated or nonirrigated. The amount of water required to produce a bushel of corn is dependent on the crop yield. If a yield of 120 bushels per acre is obtained, then 5 bushels would have been produced per acre-inch of water used in ET.

The amount of water absorbed from the soil by plants during the growing season and retained in the plant tissue at any time is less than 1 or 2% of the total seasonal ET. Most plants are not able to store water for several days as animals can. The water transpired on a minute-by-minute basis must be drawn from the soil or the plants wilt. Rainfall or irrigation must replenish the depleted soil water as the season progresses, or crop growth is reduced.

Available Water and Crop Yields

As soil water is depleted and the plants are not able to extract water from the soil fast enough to maintain the transpiration rate under given atmospheric conditions, plants lose their turgor and the stomata begin to close. Limited soil water reduces transpiration, but more important, it reduces photosynthesis and crop yields. The water available to a crop during a season varies with the amount of water stored in a soil before the season begins, the amount and distribution of rainfall or irrigation during the season, and the amount of water that soil can hold between rains or irrigations.

Water causes the greatest year to year variations in crop yields on nonirrigated lands. Severe shortages of rainfall, or long periods between rains (droughts), can drastically reduce crop yields in humid areas as well as semiarid areas.

Why Irrigate

In semiarid areas and in humid areas, farmers invest in irrigation systems to reduce the risks of low crop yields or crop failure in years of low or poorly distributed rainfall. Irrigation is used to supplement rainfall during periods of water deficiency. In arid areas, very few crops can be grown without irrigation.

Water Sources for Irrigation

Since river flows in many arid areas are highest in late spring and early summer due to melting snow in the mountains, reservoirs are used to store spring runoff for release as needed by crops. Low overwinter snowfall accummulation results in less stream flow for direct use and storage. Large reservoirs are able to store surface runoff from one year to the next. When ground water is the main source of irrigation water, water supplies usually are adequate for several consecutive years of low rainfall. Over a period of years, ground water withdrawn must be recharged by rainfall; or there will be an overdraft and ground water is said to be "mined."

Irrigation Development in the United States

The development of irrigated cropland by regions during the past four decades is summarized in Figure 2.1. Much of the irrigation development in the southwestern states and mountain states occurred before 1944. Rapid irrigation expansion occurred later in other states. The drought years of the 1950's stimulated the development of irrigation in the southern Great Plains with water pumped from the vast Ogallala aquifer. With the development of dependable center pivot sprinkler irrigation systems in the 1960's, and with ground water readily available, the area of cropland irrigated in the central Great Plains expanded rapidly in the 1960's and 1970's. The irrigated area also expanded in the humid southeastern states in the 1960's and 1970's. The total irrigated area in the United States essentially stabilized in the 1980's due to low farm commodity prices and increasing irrigation costs, particularly energy-related expenses. Irrigation costs have increased due to declining ground water levels, which increases pumping lifts and energy required for pumping, along with higher energy costs and higher costs for irrigation machinery and labor.

Economics of Irrigation

In any business, gross revenues must exceed costs. Irrigation costs represent a major portion of the annual crop production costs in arid areas. In the arid southwest, farmers are able to grow high-value crops like citrus, vegetables, and nuts because the weather is sunny, warm, and predictable. Such crop production is economical even when irrigation water is expensive.

As water costs increase, farmers invest in better irrigation systems that enable more uniform water application and greater control of the amount applied at each irrigation. They need to consider all of the variables that affect both irrigation costs and revenues. Farmers will continue to irrigate if the increased returns from higher crop yields and better crop quality due to irrigation exceed the increased farming costs associated with irrigation, and if a dependable supply of water is available.

Irrigation Systems and Water Consumption

The amounts of irrigation water applied to the soil are determined by how irrigation systems are managed. Usually, greater amounts are applied with low-cost surface (or gravity) irrigation systems than with more expensive sprinkler and drip/trickle irrigation systems. The amount of water used in ET, or depletion of water supplies within a hydrologic basin, is not significantly affected by the irrigation system. Water is consumed by the crop while irrigation systems deliver and distribute water.

Most of the excess water applied with surface irrigation methods, often mistakenly called wasted water, returns to streams or to ground water. Water that returns to the streams becomes the water supply for downstream water users. From a water supply viewpoint, a change in the irrigation system mainly affects the flow path of water in a basin and not water consumption. However, changing irrigation systems, or improving irrigation methods, may reduce irrigation costs. Exceptions of non-recoverable return flows include the following two examples. First, when water is pumped from an aquifer (overlain by a dry zone) that is not being recharged, the excess applied water is retained in the dry zone below the root zone and cannot be recovered. Second, the excess water cannot be recovered when return flows enter a saline lake from which water is not suitable for agricultural uses.

Effects of Institutions on Water Use

Institutions are involved in allocating and delivering water for irrigation. These institutions coordinate the water-related activities of water users and suppliers through a set of arrangements. Opportunities exist to improve the effectiveness of water use by institutional changes.

Development and Adoption of New Technology

Development and adoption of new irrigation technology follows the same pattern as with most new technologies. Some new technologies are adopted quickly while others may require many years for adoption. Some new irrigation technologies are still in the development stages.

Conservation Concepts

Water conservation concepts differ greatly and there is no general agreement on what constitutes water conservation. Productive discussion and development of implementation plans for effective water conservation must begin with an agreed upon definition of water conservation. An important issue that affects water conservation is reuse within regions or hydrologic basins. Water conservaton on a farm often ignores reuse possibilities, except when some farmers recycle surface runoff.

Alternative Strategies for Effective Use of Water

Several simple examples are presented to illustrate the complexity of changing irrigation practices in arid areas to release water supplies for a new, higher priority use. In semiarid irrigated areas, the two main ways to increase effective use of water are retention of all precipitation on the land and reducing evaporation by maintaining crop residues on the soil surface.

2. The Development of Irrigation

Ancient History

Ancient history shows that irrigation development was among the first man-made modifications of the natural environment that enabled people to settle in an area. Many early attempts to irrigate were rudimentary in nature, but the importance of controlling water was soon apparent for the development of society. By combining fertile land with irrigation development, nomadic tribes could settle in more stable communities, relying on crop production as a means of subsistence.

Earliest irrigation developments appear to have occurred in four major river basins: the Nile in Egypt around 6,000 B.C.; the Tigris and Euphrates in Mesopotamia around 4,000 B.C.; the Indus in India prior to 2,500 B.C.; and the Yellow River in China around 3,000 B.C. In all four areas, irrigation was developed by enclosing areas with a low dike and ponding water. Irrigation development moved from seasonal to perennial form over time. Sharing ideas and technology related to irrigation from one area to another must have occurred (Fukuda, 1976). Irrigation also was developed by the Maya and Inca civilizations in Mexico and South America more than 2,000 years ago. Irrigation continues today on many of these lands and some old facilities are still in use; for example, some of the Iranian *ganats,* or 3,000-year old tunnels for developing ground water (Kuros, 1984). Earth dams constructed in the second and third centuries in Japan for irrigating rice are also still in use, as are some 2,000-year old tanks in Sri Lanka (Takase, 1987).

The major impacts of ancient irrigation were on food supplies and populations. There were two major objectives for irrigation development. First, irrigation provided a more stable supply of food and fiber. Second, irrigation supported a higher population density. The rise of numerous early civilizations has been traced to the success of irrigation development (Dale and Carter, 1974). The success or failure of irrigation developments can be traced both to the physical and social aspects of irrigation development. Physically, inability to deal with problems such as waterlogging and resulting soil salinity caused some failures. In other cases, lack of cooperation among people in the development and operation of an irrigation system resulted in failures. These same difficulties exist in irrigation development today.

United States History

Irrigation in the United States is known to have existed among the Indians of the Southwest as early as 100 B.C. Early Spanish explorers found evidence of irrigation canals and diversion points along rivers. They also introduced the Indians to new irrigation methods and irrigated crops such as grapes, fruits, vegetables, olives, wheat, and barley (U.S. Department of Interior, 1979). In most cases irrigation allowed the Indians to develop settlements with a more secure source of food than would have been possible without irrigation.

The motivations of early settlers for irrigation development were no different from those of people of ancient civilizations. Without irrigation much of the Western U.S. was not habitable. Settlers were encouraged to form communities by developing cooperative irrigation practices. The Desert Land Act of 1877 and the Carey Act of 1894, while not very successful, were designed to stimulate private and state agency participation in irrigation development by providing public domain lands to farmers if they could develop needed irrigation. These acts indicated support for irrigation development in the West.

With some notable exceptions, such as in southern California and Utah, irrigation did not expand rapidly until the federal government became involved through the Reclamation Act of 1902. The development of irrigation was tied closely to the increased involvement of the federal government in providing the necessary capital and expertise to construct major facilities. The Bureau of Reclamation, the Army Corps of Engineers, the Bureau of Indian Affairs, and the Bureau of Land Management played significant roles in the development of irrigation in the West. Primarily through the efforts of these agencies, the irrigated acreage in the United States increased rapidly early in this century; early development occurred mainly in the southwestern and mountain states. By 1944, irrigation was well-established in the southwestern and mountain states and in the Pacific Northwest (Figure 2.1). The ability of many projects to generate and sell hydroelectric power made irrigation affordable for agricultural purposes in areas where water development costs were high.

Major expansion since 1945 has been by the private sector, resulting in rapid expansion in the central

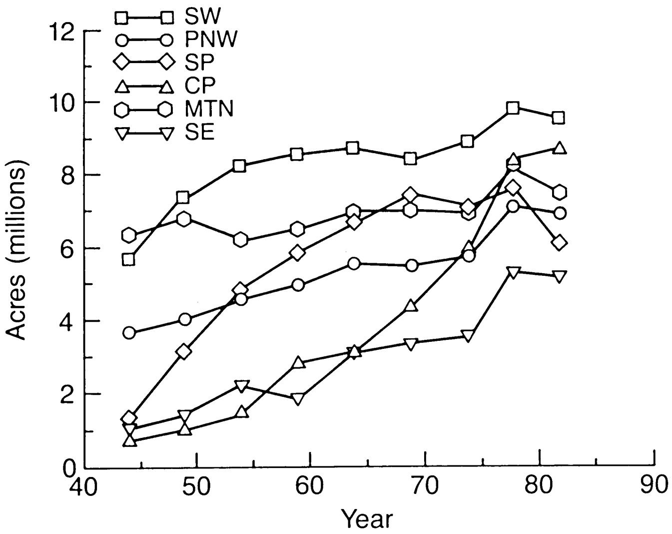


Figure 2.1. **Development of irrigated land in several regions of the United States from 1944 to 1982. Regions involve states of: Southwest (SW) = AZ and CA; Pacific Northwest (PNW) = ID, OR, and WN; Southern Plains (SP) = OK and TX; Central Plains (CP) = KS and NE; Mountain (MTN) = CO, NM, NV, UT and WY; Southeast (SE) = AL, AR, FL, GA, LA, MS, NC, and SC (U.S. Department of Commerce, 1983).**

Great Plains and in the southeastern states. This trend has changed in recent years due to low farm commodity prices, increasing pumping lifts because of declining water table levels in some areas, and increasing energy costs.

The distribution of irrigated land in farms in the U.S. is illustrated in Figure 2.2. The development of irrigation in western valleys and in areas of the Great Plains overlying the Ogallala aquifer, riceland irrigation in Arkansas and Texas, and irrigation of sandy lands in Florida clearly show the interrelation between crop water requirements, inadequate precipitation, and the importance of available ground water. Another important force behind irrigation development is the need to support the livestock industry in mountain states by irrigating pasturelands and rangelands. Without a reliable supply of forage, maintenance of a stable livestock base would not be possible during years of below normal precipitation.

World-wide Expansion of Irrigated Land

World-wide expansion of total irrigated land occurred very rapidly after 1950, increasing from about 230 million acres to about 436 million acres in 1972, an expansion rate of about 3% per year. In 1984, there were about 545 million acres of irrigated land in the world. About two-thirds of this area was in five countries (Table 2.1). The current rate of expansion has decreased to less than 1% per year (Higgins et al., 1987).

Impacts of Irrigation in the United States

Irrigation development produced many benefits in the West. Direct and indirect benefits are observable and have been documented in several case studies of irrigation projects (U.S. Department of Interior, 1979). Increased agricultural production, increased recreational opportunities, development of communities in arid regions, and hydroelectric power generation are a few of the positive attributes of irrigation. However, there also are some negative aspects, including increased federal control in communities dependent on water from federally-funded projects, adverse changes in the ecology of river basins, production of surplus agricultural commodities on irrigated land, vector-borne diseases of humans and animals, and failure of the irrigation facilities.

Emerging Issues

In discussions of the present and future development of irrigated land, a number of issues emerge. Decreasing water supplies for agriculture are of growing concern as competition for available water continues to increase. Demands for other uses of water are greater today than when the West was first settled. Some of these demands are conflicting. For example, maintaining minimum flows in rivers is now often necessary, but it may reduce the amount of water available for irrigation when these flows do not coincide with downstream crop water requirements. In addition, recreational use of reservoirs requires maintenance of higher water levels during peak use periods. Finally, water released from reservoirs for hydroelectric power production which does not coincide with downstream irrigation needs reduces the quantity that can be used for irrigation. Water evaporated to provide for fish and wildlife habitat also affects the quantity and quality of water available for irrigation and other water uses.

Declining water table levels which increase pumping lifts, coupled with increasing energy costs and low commodity prices, have made irrigation uneconomical in some areas. Depletion of aquifers and greatly reduced well yields have been major factors affecting

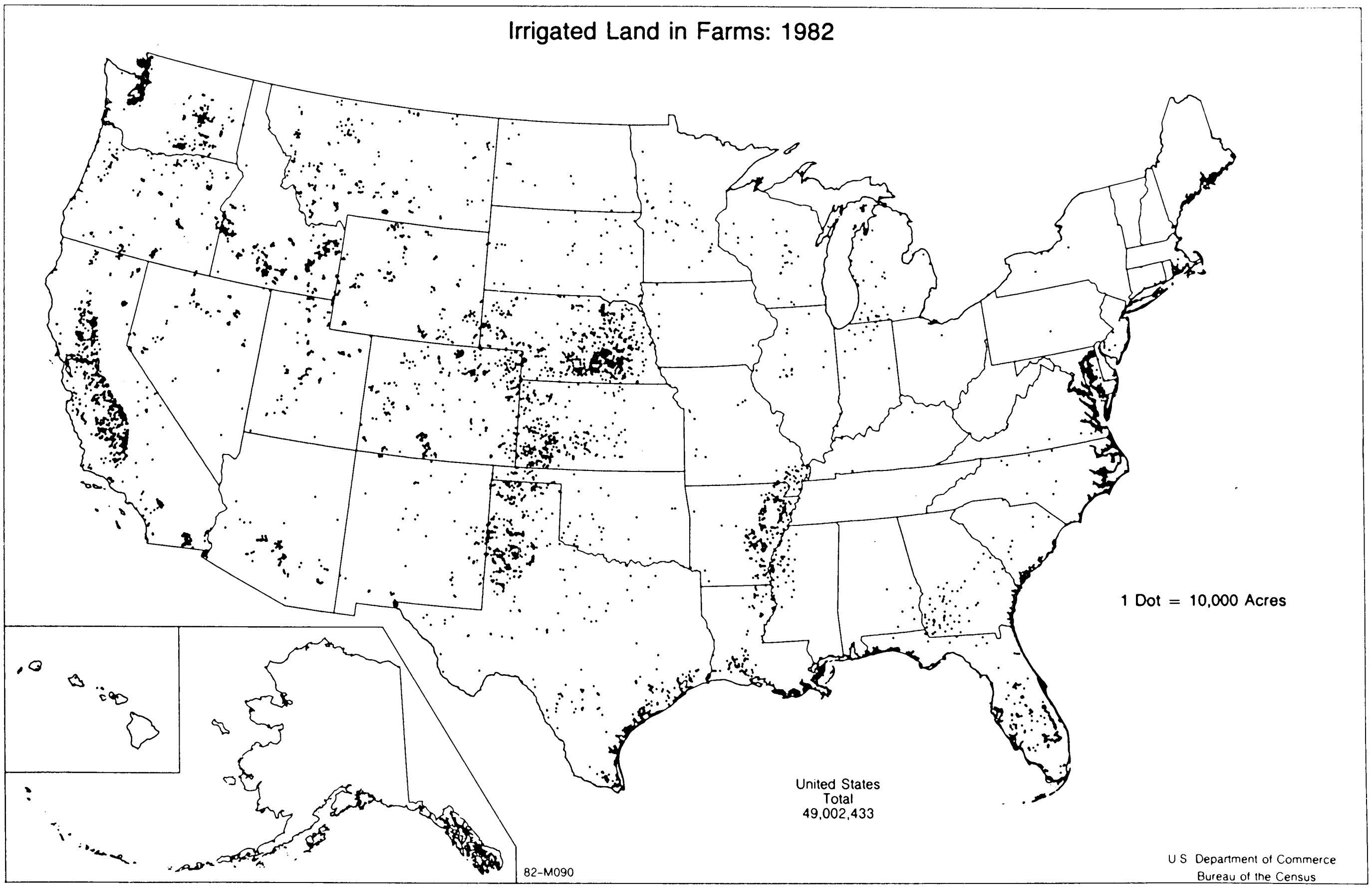


Figure 2.2. Irrigated land in farms: 1982 (U.S. Department of Commerce, 1985).

the decline in irrigated land in the southern Great Plains. The net result is that many farmers are abandoning irrigation and returning to dryland agriculture, which affects many communities economically because of decreased need for services and supplies associated with irrigated agriculture.

Poorly managed irrigated agriculture can have negative impacts on both soil and water quality. Agricultural chemicals (fertilizers, herbicides, and insecticides have been detected in some irrigation return flows. Increasing soil salinity because of rising water tables caused by inadequate irrigation water control and drainage has reduced crop productivity in some areas. The recent occurrence of selenium in subsurface drainage water from an irrigation project in California, coupled with inadequate drainage outlets to the ocean, resulted in water quality problems in the Kesterson Reservoir. Accumulation of toxic levels of selenium in marshland vegetation, and in water fowl living on this vegetation, created new and complex technical, legal, and social issues (Letey et al., 1986).

With increasing demands placed on water it is not

Table 2.1. Five countries with the most irrigated land (Food and Agriculture Organization, 1986)

Country	Irrigated area (million acres)	Proportion of total irrigated area in the world (%)
1. China	112.2	20.7
2. India	98.1	18.1
3. USA	49.0	9.0
4. Pakistan	48.2	8.9
5. USSR	37.9	7.0
All other countries	197.5	36.4
Total	542.9	100.0

surprising that increased attention is being focused on water laws at both state and national levels. Interstate conflicts over water have existed since the beginning of irrigation development; in some cases solutions have not emerged over the years. Issues related to water ownership, water allocation, and interbasin transfers are among the many legal problems at the state and national level.

Changing Irrigation Technology

In some ways irrigation technology has changed dramatically over the past fifty years; in other ways it remains basically the same. Water is supplied to farmers or the farmers develop independent water supplies. The farmers then apply the water to croplands in a manner they feel will best accomplish their goals of crop production, farm management, and lifestyle. New developments have occurred in the ways farmers can apply the water. Generally, systems that enable farmers to apply water more uniformly and more accurately than is possible with poorly designed and managed traditional surface methods require larger capital investments. Some systems also require greater technical operating skills and increased operation and maintenance costs. Labor costs normally are lower with some newer systems because of automation, but most older surface systems also can be automated.

Food Security

Irrigation projects in most developing countries are government-initiated and sponsored. Government specialists plan and construct facilities for several purposes. First, irrigation projects provide food security, clearly a national concern (World Bank, 1986). Second, in many developing countries agriculture makes major contributions to exports which generate foreign currency needed to pay for other essential imports. Thus, from a national perspective, justification for irrigation development often differs from justification by the private sector where the driving force is competition in a free market. Also, private irrigation development in a free economy must compete economically with rainfed (dryland) agriculture (Jensen, 1987).

3. Why Irrigate

Water available for plant use during the growing season is the most limiting factor in crop production and plant survival on a world-wide scale (Rosenberg et al., 1983). Optimal soil water conditions for plant growth under field conditions, even in humid areas, seldom occur. A shortage of soil water reduces crop yield and/or quality. The amount of reduction depends on the climate, the crop, the stage of growth when a shortage occurs, and on the type of soil. In arid areas, crop production generally is not possible without irrigation. In semiarid areas, irrigation will increase crop yields or quality every year.

In humid areas, irrigation may not be economical on common field crops in some years. Although most crops repond to irrigation, the increased yield may not be enough to offset the cost of irrigation. The decision to develop a water supply, purchase and install an irrigation system, and to plan on irrigating as needed is based on several factors. Key questions that must be answered in both semiarid and humid areas are whether the yield and/or quality can be improved enough, or whether the reduction in farming risks is adequate to justify a return on the capital investment and recovery of annual operating costs. In addition to the capital investment in the irrigation system, changing to irrigated agriculture may require major changes in farming operations, management, and equipment.

Climate Factors Affecting Crop Water Use

Evaporation of water requires a large amount of heat energy. About 1,000 times more heat energy is required to evaporate a unit of water than is required to raise its temperature one degree F. Daily solar radiation, the main climatic factor affecting ET, is greatest when there are no clouds. On a clear summer day, the net radiation absorbed by a field is sufficient to evaporate 0.25 to 0.3 inch of water. Solar radiation decreases with increased cloud cover. When combined with higher humidity in humid areas potential daily ET rates are lower than in semiarid and arid areas. The combined effects of higher solar radiation, drier air, and higher wind speeds result in the highest ET rates in semiarid and arid areas. The diurnal pattern of ET closely follows the solar radiation intensity as illustrated in Figure 3.1. The interception of solar radiation by clouds causes an almost instantaneous decrease in the ET rate. This relationship also illustrates that the major variable determining the ET rate is solar radiation.

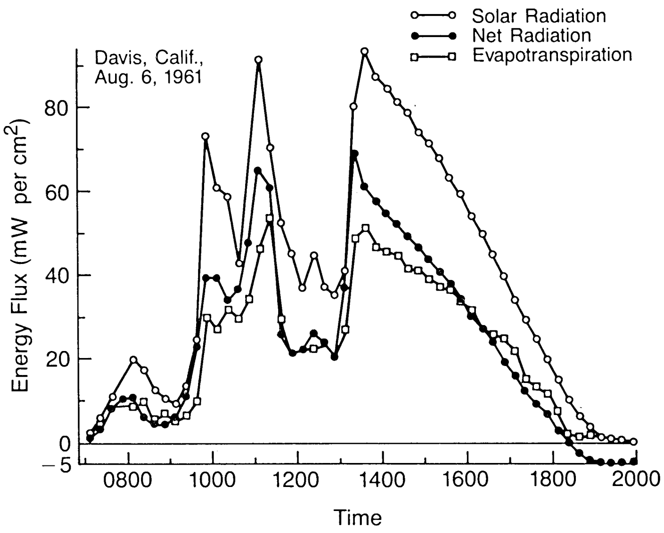


Figure 3.1. Typical diurnal variation in solar and net radiation and evapotranspiration. Evapotranspiration for perennial ryegrass, incoming solar radiation, and net radiation are expressed in energy flux terms of milliwatts per cm². There was variable cloudiness up to 1400 but clear afterward. 6 August 1961 (Pruitt, 1964).

Soil Factors Affecting Evapotranspiration

When soil water is depleted so that plants cannot extract enough water to remain turgid, the plant stomata begins to close. Closure of the stomata reduces transpiration and the absorption of carbon dioxide required for photosynthesis. The net effect of inadequate soil water is reduced crop yield and/or quality.

Physical factors affecting the productivity of a soil are its ability to hold water for extraction by plants and its barriers to plant root development. The amount of water a soil can hold following heavy rainfall or irrigation depends mainly on soil texture and is its "water-holding capacity" (WHC). The "available water," which is less than WHC, is the maximum amount of water that is available to the crop for ET. Typically, sandy soils have lower WHCs than silt or clay loam soils. Soils with low WHCs are especially likely to require irrigation to be productive.

In areas where the water table is near the root zone, water in the saturated zone can move upward by capillary action into the crop root zone where it can be extracted by plants. A shallow water table can increase the supply of water available to crops on a given soil series.

The barriers limiting full root development are shallow soils and naturally occurring hard pans or abrupt changes in texture. Soil compaction caused by machinery traffic also can affect root development.

The surface characteristics of soils affect their ability to infiltrate rainfall, particularly during intense rains. Soils with high water-holding capacities often have low infiltration rates. As a result, significant portions of rainfall may run off a field instead of replenishing the depleted soil water. Tillage and crop residue management practices can maintain the infiltration rate near its maximum and can reduce evaporation losses (Phillips, 1984). Tillage also affects the surface roughness, allowing water to be retained on the surface longer, thereby increasing the amount infiltrated. Retention of crop residues on the surface maintains the intake rate by protecting the soil surface from raindrop impact, and it decreases the absorption of solar radiation and increases the resistance to evaporation (Zobeck and Onstad, 1987).

Crop Factors Affecting Evapotranspiration

Before plant seedlings emerge and during the seedling stage, evaporation from the soil dominates ET. As the seedlings develop and leaf area expands, transpiration increases until the leaf area (one side) is about three times the surface area of soil, then the rate of ET for a well-watered crop is controlled mainly by climate. Water transpired by crops must be extracted from the soil essentially at the same rate as it is transpired or the plants wilt. Wilted plants and closed stomata reduce photosynthesis, accumulation of dry matter, and marketable crop yield. Because of this close relationship, transpiration and photosynthesis in a given climate are closely related and proportional to crop yield.

The total ET for a crop in a season depends on the climate and length of the crop's growing season. Crops which develop leaf area slowly, or have limited leaf area, and/or mature before the end of the potential growing period have lower total season ET values than crops which develop leaf area rapidly and continue to grow throughout the potential growing season. For example, a crop of field beans planted in rows late in the season usually matures before the end of the potential growing season. As a result, the total ET is much less than that from a pasture or forage crop which begins to grow in the spring, is well-watered, and continues to grow until the air temperature decreases to the lower limit for growth in the fall. Typical rates of ET during various growth stages for several crops are illustrated in Figure 3.2.

CROP	DATE	ETcrop	ETp
Grass	Annual	--	51.8″
S. Beets	3/25-9/20	33.5	38.4
S. Beets	6/15-11/3	23.8	28.6
S. Beets	6/15-3/15	31.1	35.3
Tomatoes	4/30-9/24	26.8	34.1
Beans	6/21-9/24	15.9	22.4
Corn	5/15-9/20	25.2	30.5
Barley	11/1-5/31	15.1	19.8

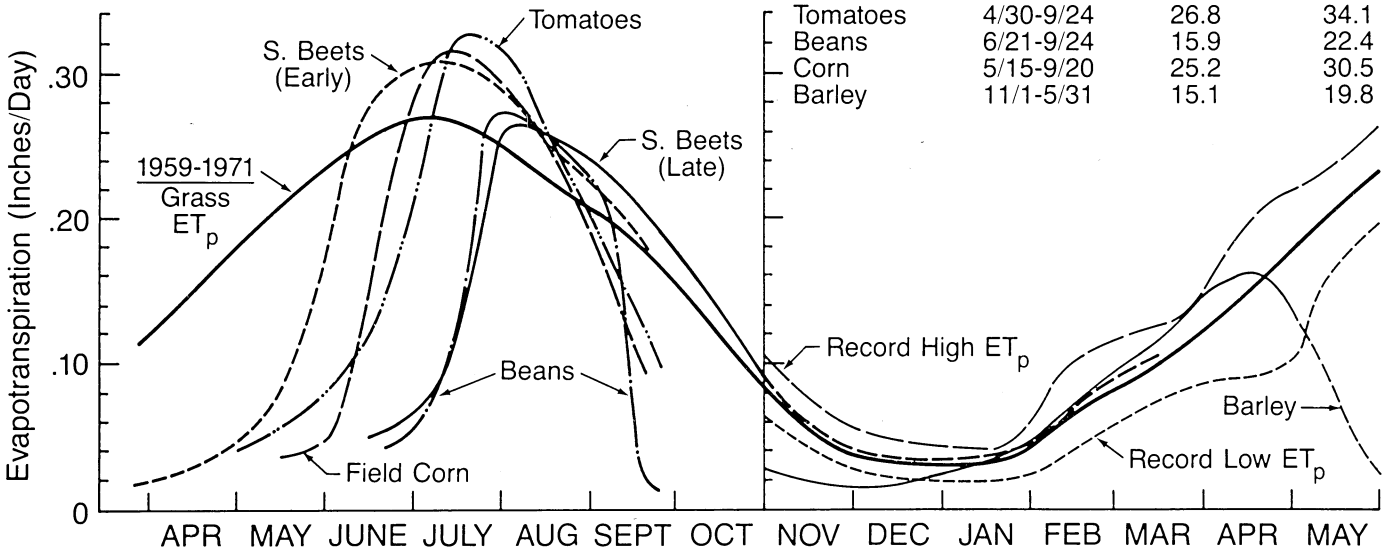


Figure 3.2. Typical curves illustrating the average rates of evapotranspiration by various crops grown in California. Seasonal totals are represented by the area under each curve (Pruitt, 1972).

Crop Yield and Evapotranspiration

Crop yields also are affected by other variables such as available plant nutrients, weeds, insect control, diseases, and cultural practices. The crop cultivar, or variety, and plant density also affect crop yields. However, if water is the limiting factor, its effects usually dominate crop yield. Assuming that other growth variables are maintained near their optimum, there is generally a linear relationship between ET and crop yield because of the photosynthesis-transpiration relationship.

Most crops tend to be more sensitive to soil water deficits at certain "critical" growth stages. Typically, soil water deficit during the flowering and heading growth stages is more damaging than when stress occurs during vegetative stages. For example, Eastin et al. (1984) in Nebraska reported plant stress occurring at the beginning of the flowering stage for grain sorghum reduced yields less than 10%; however, stress during the period from flower formation to pollen formation reduced yields nearly 30%. From pollen formation to full bloom, plant stress reduced yields about 20% while stress the first week after full bloom reduced yields about 15%.

The yield of the marketable product per unit of water used in ET also varies with the crop species. For example, under limited soil water conditions, grain sorghum, a drought-tolerant crop, in one case produced 6.1 bushels per acre-inch of water used compared with 3.9 bushels per acre-inch for corn, a drought-susceptible crop. Under well-watered conditions, corn will produce as much grain per unit of water used in ET as grain sorghum. Effective water management involves not only optimal timing and amount of irrigation, but also selection of the best crop for expected available water supplies and climate-soil characteristics.

Reducing Farm Risks and Other Benefits

The primary purpose of irrigation in semiarid and humid areas is to supplement rainfall. Irrigation lessens the risk of low crop yields caused by inadequate soil water. Irrigation also reduces other farming risks. For example, when surface soil water is limited, germination of seeds and emergence of the seedlings is often nonuniform which reduces crop yields. With irrigation, the probability of a uniform stand is greatly increased, enabling the farmer to avoid overplanting and wasting fertilizer.

In arid areas, establishing a small-seeded crop is essentially impossible without irrigation. In some arid areas, portable sprinkler irrigation equipment is installed to enable very light, frequent applications of water until seedlings have been established. Then the sprinkler equipment is removed and normal surface irrigation is used for the balance of the growing season. Irrigation also enables planting on optimum dates so that the crop can be ready for harvest when the market prices are best.

Irrigation is essential in establishing transplants of high-value crops such as strawberries, lettuce, or bare-rooted plants. Irrigation also is used to control wind erosion on sandy land in windy areas until plant growth can be established and to reduce high soil temperatures when establishing a crop during the summer. In a few instances irrigation, which causes wetting and resultant cooling, is used to reduce the temperature of sensitive plant parts under hot, dry conditions. In fruit-growing areas, irrigation in the spring has been used to cool buds, thus delaying flowering until the risk of a late spring freeze decreases.

Irrigation has been used for frost/freeze protection in the U.S. for more than a half-century (Howe, 1935). When water freezes it releases about 144 times more heat energy (heat of fusion) than that required to raise its temperature one degree F. When air temperatures drop below 32° F and adequate irrigation water is applied, the plant parts remain at 32° F as ice forms. For freeze protection, water must be applied continuously during the freezing period. Crops routinely protected from freeze damage by sprinkler irrigation are citrus and other tree fruits, small bush fruits, some vegetable and nursery crops, and seedling beds.

Controlling Crop Quality

The quality of the marketable component of a crop is especially important in high-value or specialty crops like citrus, vegetables, and strawberries. Cotton grown under irrigation typically will have longer fiber length and greater fiber strength. Irrigation can reduce the susceptibility of some crops to diseases resulting from severe water stress. Typical examples include black heart disease of celery and blossom end rot on tomatoes, pepper, and eggplant. Quality factors controllable with irrigation are cracked fruit, misshapen fruit, rot, color, taste, firmness, sugar content, and poorly filled out tips on sweet corn ears. On the other hand, over-irrigation can have detrimental effects on quality of some crops and increase the susceptibility to some crop diseases.

4. Economics of Irrigated Agriculture

Irrigation is practiced where the benefits, however defined, outweigh irrigation costs. These benefits include: (1) increased and predictable yields; (2) improved crop quality; and (3) reduced farming risks. The irrigation system and practices used depend on economic, physical, and biological variables. Farmers attempt to manage inputs such as water, fertilizer, labor, and machinery in order to maximize profits or net returns from their operations. Where irrigation is included in crop production, the amount and manner of water application can significantly influence net returns.

Economic principles of crop production require combining inputs to maximize net benefits. Optimal amounts and timing of irrigations depend on economic, biological, physical, and social variables. Principle economic variables include: the price of water, the cost of applying water, and the price the growers receive for their crops. In general, the optimal quantity of water applied will be larger when the price of water is lower, other things being equal. Conversely, the optimal amount of water will be larger when the value of the crop irrigated with that water is higher. The optimal level of applied water depends on the crop water production function which expresses the general relationship between the amount of applied water and yield. The optimal amount of water applied during the season results when the economic return from the next increment of water applied equals the incremental cost of applying that next unit of water. Management, including timing of irrigations and amount applied at each irrigation, are critical factors affecting crop yield and irrigation cost. Most crop water production functions normally do not incorporate the quality of the crop, which also can affect the price received. Crop water production functions serve only as a guide because the timing of irrigations usually is not considered.

Irrigation Management

Irrigation water is applied in discrete amounts and times with most irrigation systems. The soil acts as a water reservoir, or bank, providing a water supply that plants can use during periods between rains or irrigations. The optimal pattern of irrigations requires consideration of the expected rainfall before the next irrigation, the timing of the next irrigation, and the maximum amount of water that the soil can hold at the time of irrigation. The uncertainty of rainfall in humid areas makes irrigation scheduling more difficult.

In arid regions where most of the water used in ET is supplied by irrigation, a well-managed irrigation regimen usually avoids plant water stress at critical stages. However, unlike ET, applied water (AW) is controlled by the farmer. The yield-AW relationship differs from the yield-ET relationship when all of the applied water is not retained in the soil. The variables affecting the amounts retained are closely related to irrigation uniformity and the amounts applied at each irrigation.

Irrigation Uniformity

The desirable irrigation system is one that uniformly applies a specific amount of water over a field, and applies water at a rate low enough so that all of the water infiltrates. Farmers who have irrigation systems that have poor uniformity characteristics must balance overirrigating parts of the field with under-irrigating other parts. For example, if a depth of four inches is needed to replenish the plant-available water that has been used in ET, the farmer can only attain this objective over the entire field by applying an average of more than four inches. The excess water percolates below the root zone and is called deep percolation (DP). On the other extreme, if only the parts of the field receiving most the water receive four inches, the rest of the field would be underirrigated.

The uniformity at which an irrigation system applies water is characterized by a "uniformity coefficient." The most commonly used uniformity coefficient is the Christiansen's Uniformity Coefficient (CUC) (Christiansen, 1942). It is based on the deviations of applied water within a field from the average depth applied.

Using crop yield-water deficit relationships, the effect of irrigation uniformity on the average yield of a crop is illustrated in Figure 4.1. In this example, the average yield of corn versus the average depth of water applied during the season is shown for irrigation systems applying water at several uniformity levels (Letey et al., 1984). A low CUC value indicates that water is applied nonuniformly. A high CUC value indicates uniform water applications and soils. In this example, it was assumed that the management practices involving the timing and amount of water applied at each irrigation were near optimum.

The solid line labeled "uniform" in Figure 4.1 represents what could be accomplished on a carefully-

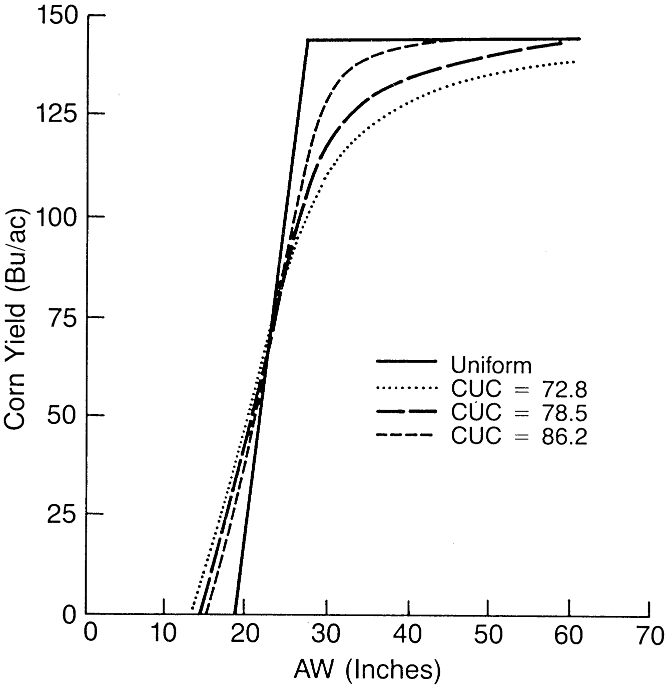


Figure 4.1. Example hypothetical relationship between corn grain yield and applied water (AW) for various levels of irrigation uniformity, as indicated by Christiansen's Uniformity Coefficient (CUC) (Letey, Vaux, and Feinerman, 1984).

managed small plot for which the applied water-yield curve (AW-yield) is the same as the ET-yield curve until the maximum yield is attained. The leveling off of the curves at the higher yields indicates that if ET has not been reduced, no further increases in yield occur with additional water applications.

Generally, the cost of an irrigation system increases as its potential uniformity increases. With a lower cost system that applies water less uniformly, the costs of applying more water is partially offset by increased crop yields. The optimal system and water applications that maximize profits for the farmer depend on the relative water costs, the level of management, the costs for the irrigation system, and the prices received for the crops to be grown on the field. The estimated optimum water applications for the previous example are illustrated in Figure 4.2. In this example, the assumed price for corn was $130 per ton for $3.64 per bushel. The curves shown in Figure 4.2 indicate that when the price of water is low and with lower system uniformities, more water must be applied than ET to maximize profits. Under these conditions, the profit-maximizing water application is usually much more than the maximum ET for the crop.

The curves in Figure 4.2 indicate the amount of water applied to maximize profits, but does not show the level of profit. Generally, the level of profit decreases with decreasing uniformity because of the higher total cost of applying water and lower revenue from reduced yields. Therefore, the farmer can sometimes justify capital investment to upgrade an existing system or to improve the level of management which generally improves the uniformity.

Salinity Considerations

All irrigation waters contain some dissolved salts. Salts in irrigation water become more concentrated in the soil because ET moves essentially "pure" water leaving the salts in the remaining soil water. To prevent yield reduction or salt damage to the crop, some water in excess of that required for ET must be applied so that salts that have accumulated will be moved (leached) below the root zone. The amount of leaching required depends on the salt concentration in the irrigation water (in turn dependent on the water source) and the sensitivity of the crop to salinity.

Figure 4.3 illustrates the general relationship between the yield of one crop (corn) and the relative amount of water applied (AW) divided by the amount of water evaporated (Ep) from a Class-A evaporation pan (AW/Ep) (Letey and Dinar, 1986). The curves in Figure 4.3, which do not include uniformity effects, show that at a given level of applied water, corn yield

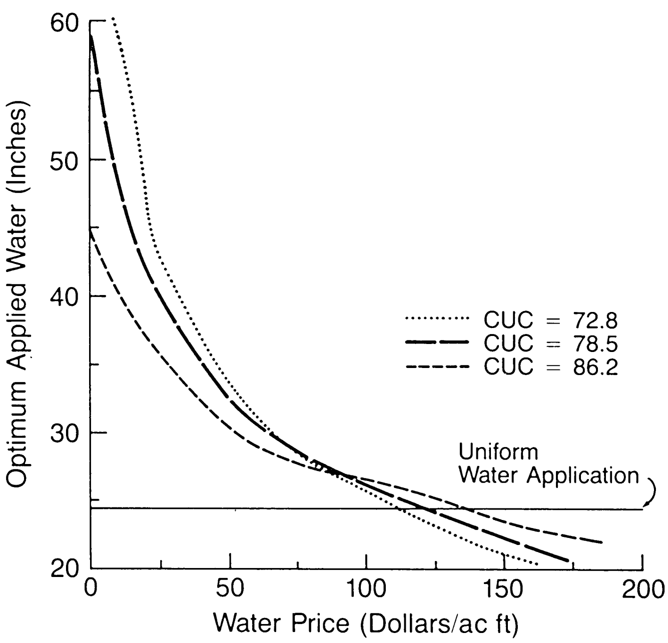


Figure 4.2. Example relationship between applied water (AW) and water price for various levels of irrigation uniformity for corn, as indicated by Christiansen's Uniformity Coefficient (CUC) (Letey, Vaux, and Feinerman, 1984).

decreases as salinity levels increase. Increasing the amount of applied water increases yields because of greater leaching of salts from the root zone. The general shapes of the curves are similar to those for nonuniform irrigation so that, as before, optimal irrigation management requires balancing increasing applied water at each irrigation, which increases costs, with increasing yields expected.

The curves presented in Figure 4.3 vary for different crops depending on their tolerance to salinity. If the water is very saline, salt-sensitive crops, such as lettuce usually require water applications much in excess of ET to maximize profits.

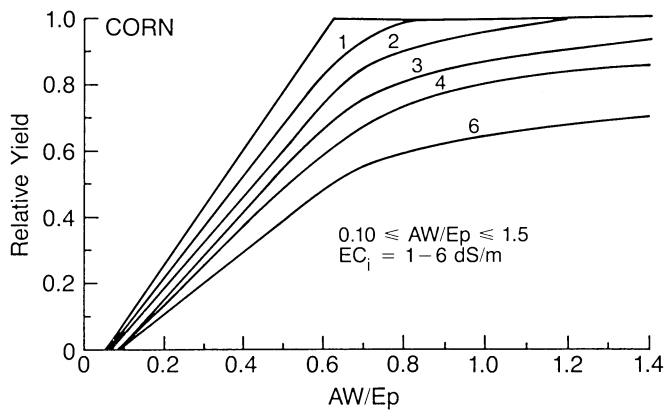


Figure 4.3. Example relationship between the relative yield of corn and applied water (AW) divided by pan evaporation (Ep), and water at five increasing levels of salinity (Letey and Dinar, 1986).

Uncertainty in Optimal Irrigation

Crop production functions involving applied water are affected by many factors that cannot be accurately characterized and which may change from year to year. With some surface systems, the farmer has less control of the amount of water applied during irrigations than with sprinkler or drip systems. As previously stated, irrigation uniformity greatly affects optimal irrigation depending on the crop-water production function (Figures 4.1 and 4.2). Yet the irrigation uniformity may not be known accurately by the farmer (Letey, 1985). As a consequence, there is a significant degree of uncertainty associated with applying production functions for each crop.

Water application patterns also vary with each irrigation, especially with sprinkler systems, which are affected by wind speed and direction. Typically, the seasonal uniformity of a sprinkler system tends to be higher than the uniformity of a single irrigation because of the random effects of wind on the distribution pattern (Pair, 1968). Even rainfall is not uniform across a large field when most of the rain occurs during thunderstorms. Because of these uncertainties, and because the negative effects of overirrigation on crop yields tend to be less than the effects of underirrigation, there is a systematic bias for overirrigation.

Different irrigation systems described later in this report enable applying various amounts of water with different degrees of accuracy and uniformity, with a corresponding increase in management inputs. Most surface systems do not provide as accurate or as uniform irrigation as that obtained with pressurized irrigation systems because surface systems depend on the surface of the soil as both the conveyance channel and infiltration surface. Soil conditions change during the season and management must adjust for these changes. Moving sprinkler, spray, and trickle systems usually apply water more uniformly than stationary systems because each outlet is a line source instead of a point source. However, pressurized systems usually are more expensive than surface systems.

The farmer must make a decision as to whether the costs of new or improved irrigation systems providing better water control can be offset by benefits such as higher yields and/or reduced water application costs. When the cost of water is low, it may be less expensive to apply more water than to increase the level of management or upgrade the system. From the farmer's perspective, applying more water than that required for ET is not inefficient or "sloppy." It may represent a sound decision based on a management objective of maximizing profits or minimizing the likelihood of losing the right to that water in the future.

From a water supply viewpoint, if the applied excess water returns to the ground water or back to the original stream, major changes in irrigation systems will have little effect on overall water supplies. Only the flow path and alternative gravity diversions are affected in most cases. In some areas, however, excess applied water may pick-up salt from underlying saline formations. In such cases, changes in management or in the irrigation systems to reduce return flows would benefit downstream water users. However, the upstream farmers who change management of systems may receive little or no direct benefit depending on the current level of management. If management inputs are low, increased yields and reduced costs can result from changes in management or systems. Some of these aspects are externalities related to irrigation management.

Externalities Related to Irrigation Management

An "externality" arises when some of the costs or benefits of irrigated agriculture accrue to society as a whole, and the costs (as reflected in market prices) are not borne by farmers or by consumers of their products. Many of these externalities are associated with irrigation water storage reservoirs, return flow to streams from surface runoff and deep percolation, and deep percolation to the ground water.

Society benefits when return flows serve other beneficial uses such as recharging aquifers, enhancing wildlife habitat, stabilizing stream flow during summer months, and providing boating and fishing recreation. These are positive externalities. On the other hand, if return flows contain large amounts of sediment or toxicants such as selenium or agricultural chemicals, they impose a cost to society by contributing to surface and ground water pollution and they create negative externalities.

During the past few decades increasing water quality degradation has been observed. Recently, increased attention has been focused on ground water quality. The general public perception is that there may be greater negative than positive externalities associated with irrigated agriculture because of water quality issues. Some negative externalities are associated with the application of fertilizers to provide plant nutrients and pesticides to control weeds, insects, and plant diseases. Optimal fertilizer application is based on the current plant nutrient status of the soil, crop yield-fertilizer production functions derived from plot experiments and soil tests, the cost of the fertilizer, and the expected price of the crop product. Crop yield-fertilizer production functions are similar to crop water production functions. For example, yield increases usually are proportional to the first few increments of nitrogren application, and the yield response plateaus at higher levels because nitrogen no longer is a limiting variable. With low fertilizer costs, the optimal amount is near that which will result in maximum yield. Applying nitrogen to achieve maximum yield requires applying more nitrogen than is taken up by the crop. The excess provides a potential source of nitrogen pollution because nitrogen in the nitrate form is soluble and moves with soil water.

Other agricultural chemicals may persist in the soil and water and can be transported by water, thus leading to surface and ground water pollution. Water quality degradation from fertilizers and other agricultural chemicals is an externality related to management of both irrigated and nonirrigated agriculture.

Water quality degradation is not always associated with the application of agricultural chemicals to crops and soils. For example, excess water percolating below the root zone of irrigated land in the Grand Valley of Colorado passes through formations containing large amounts of soluble salts. As the percolating water dissolves some of the salts, the saline return flow to the Colorado River degrades the quality of water in the river.

Drainage waters from some areas on the west side of the San Joaquin Valley of California contain naturally occurring selenium and other potentially toxic trace elements which, when in excess, can be detrimental to biological systems (Letey et al., 1986). These elements are of geologic origin and are not related to the application of farm chemicals.

The above two examples illustrate that the type and magnitude of externalities associated with irrigation are highly variable and site-specific. If the costs of these externalities are imposed on the farm managers through regulations, taxes, or some other means, the optimal management of irrigation water and the profitability of the farm operation may be altered significantly. For example, one study showed that the optimal applied water and profits associated with growing cotton varied with irrigation unifor mities and drainage water disposal options (Dinar et al., 1985). Three hypothetical cases were evaluated:

1. Water percolating below the root zone was free to move and imposed no cost or benefit to the farmer.
2. Water percolating below the root zone was imped-ed by an impermeable layer which required the farmer to install a subsurface drainage system and the drainage water could be disposed of without a cost to the farmer.
3. Same as Number 2, except drainage water had to be disposed of on the farm using evaporation ponds.

The applied water that produced the optimal yield and associated profits are summarized in Table 4.1. The profits were defined as returns to land and management and are dependent on the sale price of cotton. The relative profits associated with the above three cases indicate that in the first case, the optimal water application increases as uniformity (Christiansen's Uniformity Coefficient) decreases from 100 to 72 because the resultant deep percolation does not impose a cost on the farmer. An increase in CUC from 72 to 100 increases the profits to the farmer if the costs of upgrading the system and management are not considered.

Table 4.1. Optimal applied water (AW) and associated profit (Pf) for cotton produced under various management conditions expressed as relative values[a]

CUC	AW,Pf	Case 1 No drainage requirement	Case 2 Off-farm disposal	Case 3 On-farm evaporation ponds for disposal
100	AW	100	100	88
	Pf	100	100	98
86	AW	125	113	88
	Pf	98	98	88
72	AW	175	163	100
	Pf	92	91	71

[a]Relative values based on Christiansen's Uniformity Coefficient (CUC) = 100. At CUC = 100, AW = 31.5 inches, and P = $550 per acre (Dinar et al., 1985).

In the second case, the optimal water applied and associated profits are similar to those in the first case. In case three, significant shifts in irrigation management and profitability are associated with a drainage requirement and the high drainage costs due to on-farm evaporation ponds. Both applied water and profits are reduced significantly as irrigation uniformity decreases. In this case, a substantial investment could be made in upgrading the irrigation system and level of management to enable applying water more uniformly.

Irrigation Management Strategies

The management strategy for an irrigated farm is largely dictated by what crops are produced and how much water is allocated to each crop. The net income for many irrigated farms is comprised of four potential sources: (1) net income from the irrigated land; (2) net income from nonirrigated land (dryland); (3) net income from other land resources; and (4) the net income from the excess water resource. The optimum strategy (if it can be determined) is called "land limited" if all the available land can be irrigated and enough water is available to meet the irrigation allocation. The strategy is called "water limited" if all the irrigation water is allocated and enough land is available to meet the land allocations, and "crop limited" if crop production is simply not profitable (because production costs for possible crops are greater than the returns).

An economic analysis of these alternatives is difficult because the relationships of yield to the amount and distribution of irrigation water are complex, as previously discussed. Also, costs associated with saline irrigation water include off-site (or disposal) costs, while dryland production is largely dependent on rainfall and other unpredictable factors. Irrigated production also is affected to some degree by these factors.

Management with Limited Land

When land is the limiting resource, management strategies attempt to maximize the return on investment per unit land area. When ample irrigation water is available, the amount of irrigable land limits the net return. Then the primary planning decisions are the optimal amount of each crop to grow and the optimal amount of irrigation to apply to each crop. This problem has been analyzed for specific cases (Dinar et al., 1985; Hart et al., 1980; Martin et al., 1984; Seginer, 1978; 1983).

Although the optimum amount of water to apply to a specific crop mix for the limited land situation depends on many factors, some general trends are apparent:

1. As irrigation uniformity increases, the optimum amount of irrigation water will decrease.
2. For a given water uniformity, the optimum application amount will decrease as the water price increases.
3. With an increase in irrigation water salinity, the optimum irrigation application will increase.
4. Where drainage is necessary, the optimum irrigation will decrease slightly from a situation where no subsurface drainage is necessary. The amount of decrease is dependent on the cost for drainage water disposal.

Management with Limited Water

When the available water supply is limited, planning decisions include the mix of crops, the amount of each crop to irrigate, and the amount of water to use for irrigation of each crop. These complex decisions are further complicated by the uncertain nature of rainfall and crop ET. Most irrigated lands in the southwestern and southern United States and Southern Great Plains have limited water. Analysis of limited-water management by Seginer (1983), Martin et al. (1984), and others can be generalized as:

1. Larger irrigation amounts should be used when the potential to increase yield is very large, or when land-associated production costs are large relative to the income potential.

2. If land-associated production costs are small, then the available water should be spread over a large area (limited by some minimum application amount).

3. If land-associated production costs are large, the optimum irrigation amount should increase (intensify the irrigation).

5. Water Sources for Irrigation

The Natural Water Cycle

Water is a renewable and essentially indestructible resource. It occurs as a liquid, vapor, or solid (ice). Its natural occurrence as a liquid is highly variable with location and time. Evaporation, transport of water vapor, precipitation, and flow of water over the earth's surface are known as the hydrologic cycle (Figure 5.1). Evaporation occurs from the oceans, lakes, wet soil and plant surfaces, and from growing vegetation (transpiration). Water returns to the earth's surface as rain or snow.

The variation in precipitation over the United States is caused by atmospheric circulation patterns, variations of solar warming of the earth's surface (a cause of local summer thunderstorms), and the effects of hills and mountains (as air masses are forced over hills and mountains, moist air is cooled until some of the water vapor changes to liquid or ice and falls as rain or snow). The average annual precipitation in the United States is shown in Figure 5.2.

Disposition of precipitation is affected by land surface conditions. Most of the land surface is covered by a soil mantle developed from weathered rock or from wind or water deposits. Two soil characteristics that especially affect the hydrologic cycle are the infiltration rate — the rate water enters a soil — and water-holding capacity — the amount of water a unit volume of soil can retain against the force of gravity. The water-holding capacity is related to the amount of water that can become available for plants — available water. Excess infiltrated water percolates to the ground water. When the rainfall rate exceeds the infiltration rate, surface ponding or runoff occurs.

Most surface runoff occurs during and after intense storms. Much snowmelt also becomes runoff because the underlying soil mantle often is saturated or frozen. Rainfall runoff enters stream channels and flows to lakes and rivers. Under natural conditions, much of the surface runoff returns to the oceans. Except on level lands, surface runoff may be completed in a few hours after a rain. Precipitation which has accumulated as snow may not contribute to streamflow until prolonged, above-freezing temperatures occur in the spring and early summer. Also, stream flow from snowmelt continues for long periods because of the gradual melting process. The average annual runoff in the U.S. is shown in Figure 5.3.

Water that percolates through the soil and accumulates in voids in the underlying rocks comprising the earth's mantle is called ground water. Aquifers are geological formations in which water accumulates. They are porous enough so that water can move relatively freely. Large aquifers that yield water to wells at a rate sufficient to be economically useful are shown in Figure 5.4. When the water surface in an aquifer is at atmospheric pressure, it is called the water table. When ground water is confined under pressure by impermeable layers such as tight clay lenses, the aquifer is said to be artesian or under artesian pressure.

When the water table near a stream is at a higher elevation than the surface of the stream, ground water flows toward and seeps into the stream channel. This water maintains the flow of streams between storm runoff events. When the water table is below the water level in the streams, water may flow from the stream to the aquifer. Streams in such areas usually flow only after storms producing surface runoff or during periods of snow melt.

Ground water aquifers are depleted by pumping and are recharged by precipitation and/or irrigation water percolating beyond the plant rooting depth. If withdrawal of water from an aquifer does not exceed the average recharge rate, the rate of withdrawal is called the safe yield. If the average annual pumping rate exceeds the average, long-term recharge rate, the aquifer is said to be "mined."

When energy from solar radiation and the atmosphere that is available for ET exceeds precipitation on a 5- to 10-day basis, there is little surplus water left to percolate through the soil and recharge aquifers. Conversely, in areas where seasonal precipitation exceeds ET, water is available to recharge ground water aquifers or supply surface streams.

Major components of the water cycle, or water budget, for the United States are shown in Figure 5.5. The average annual precipitation received by the contiguous 48 states is 4,700 million acre-feet (MAF) per year. The "consumptive use" component as defined by the U.S. Water Resources Council (1978) is water withdrawn for offstream uses and not returned to a surface-water or ground-water source.

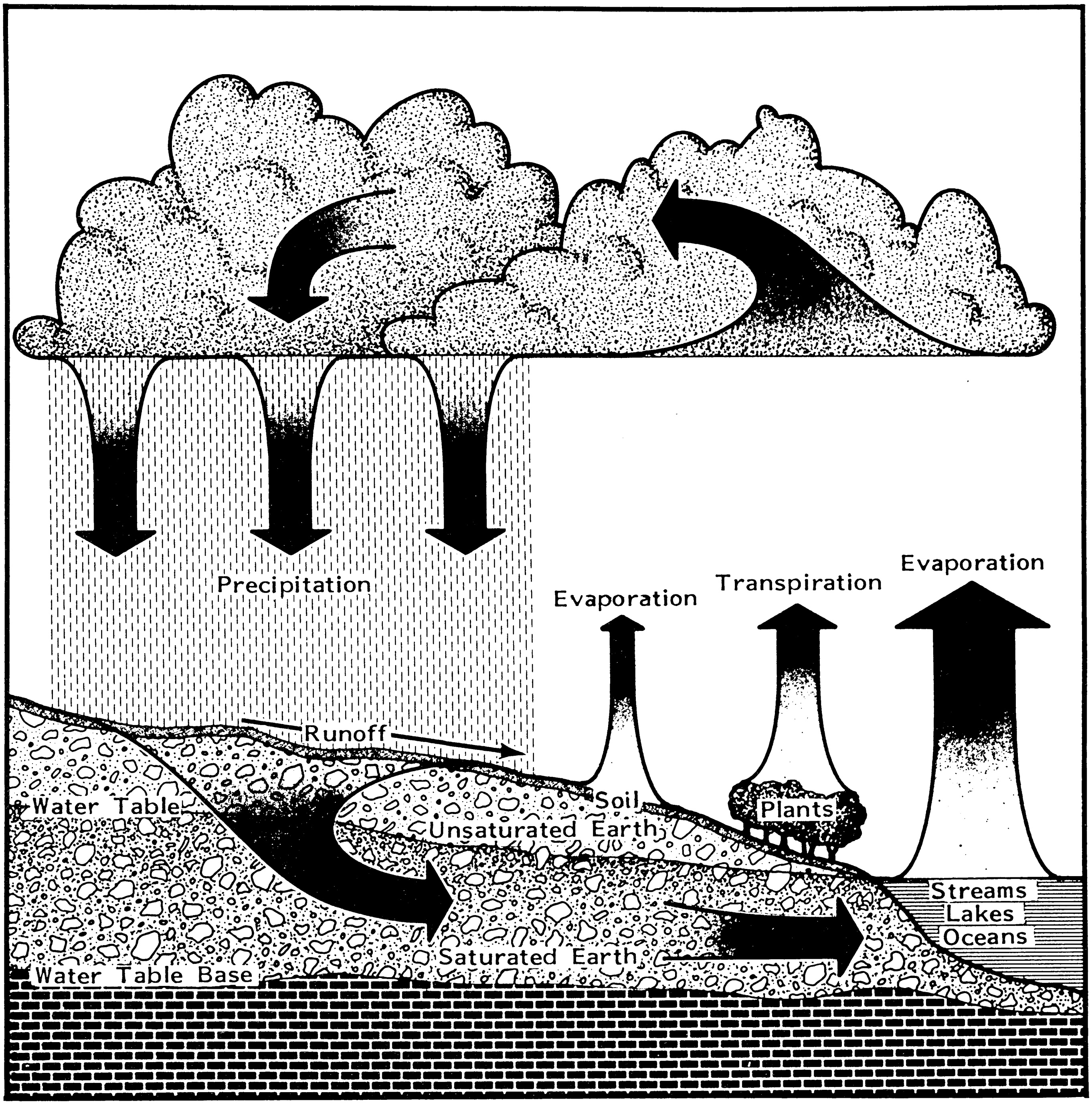


Figure 5.1. The hydrologic cycle. Drawing by Rex D. Heer, Iowa State University, Ames, Iowa.

Precipitation

The largest annual precipitation is in the Pacific Northwest and along the Pacific and Atlantic Oceans. The annual precipitation decreases from the Atlantic Ocean towards the Rocky Mountains. The heavy precipitation in the Rocky Mountains occurs mainly in the winter as snowfall which serves as a natural storage reservoir for water until the snow melts. Melting snow at high elevations, which begins in the spring and continues into midsummer, prolongs the runoff.

The general pattern is for winter precipitation west of the Rocky Mountains; summer precipitation in the Great Plains; and nearly uniformly distributed precipitation throughout the year in the eastern states except in the southeastern states.

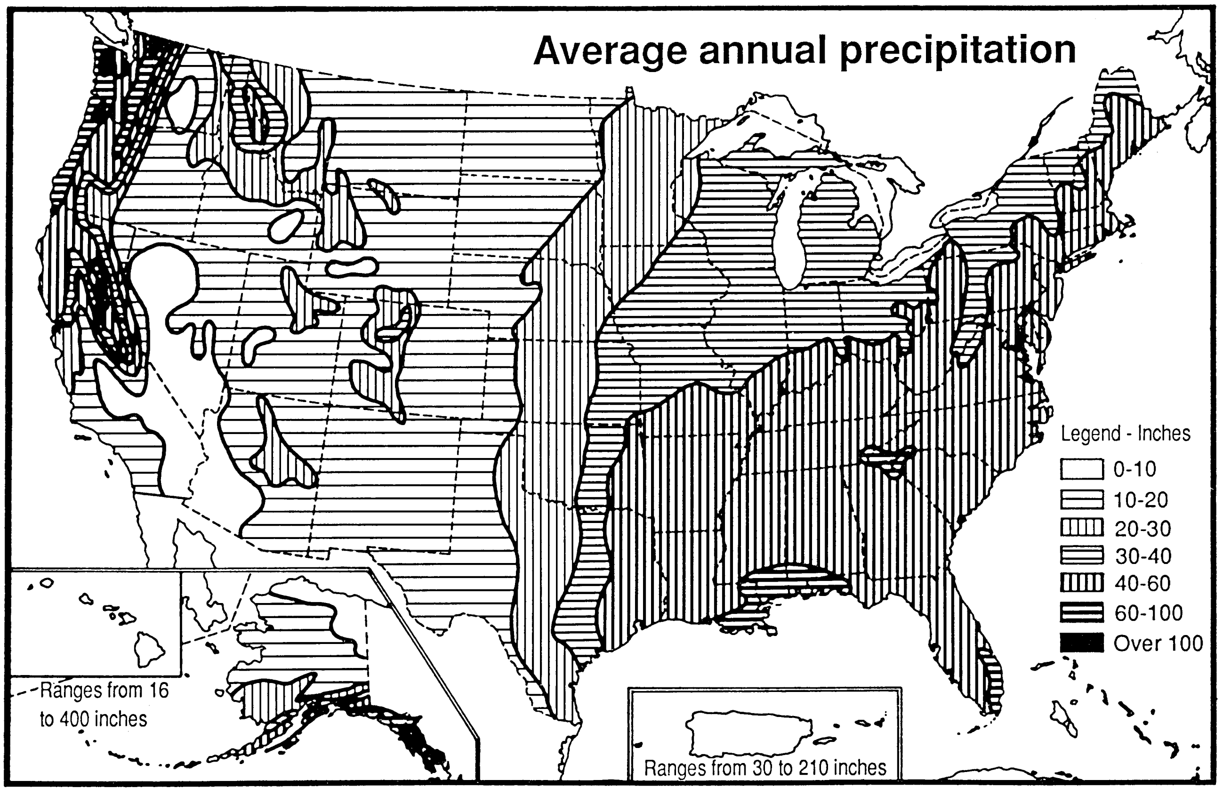


Figure 5.2. Average annual precipitation in the United States (U.S. Water Resources Council, 1978).

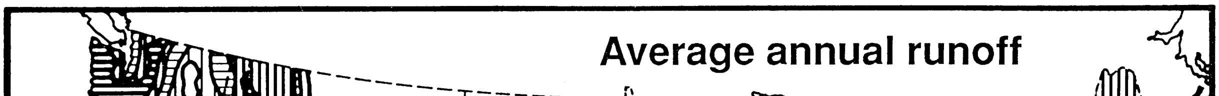


Figure 5.3. Average annual runoff in the United States (U.S. Water Resources Council, 1978).

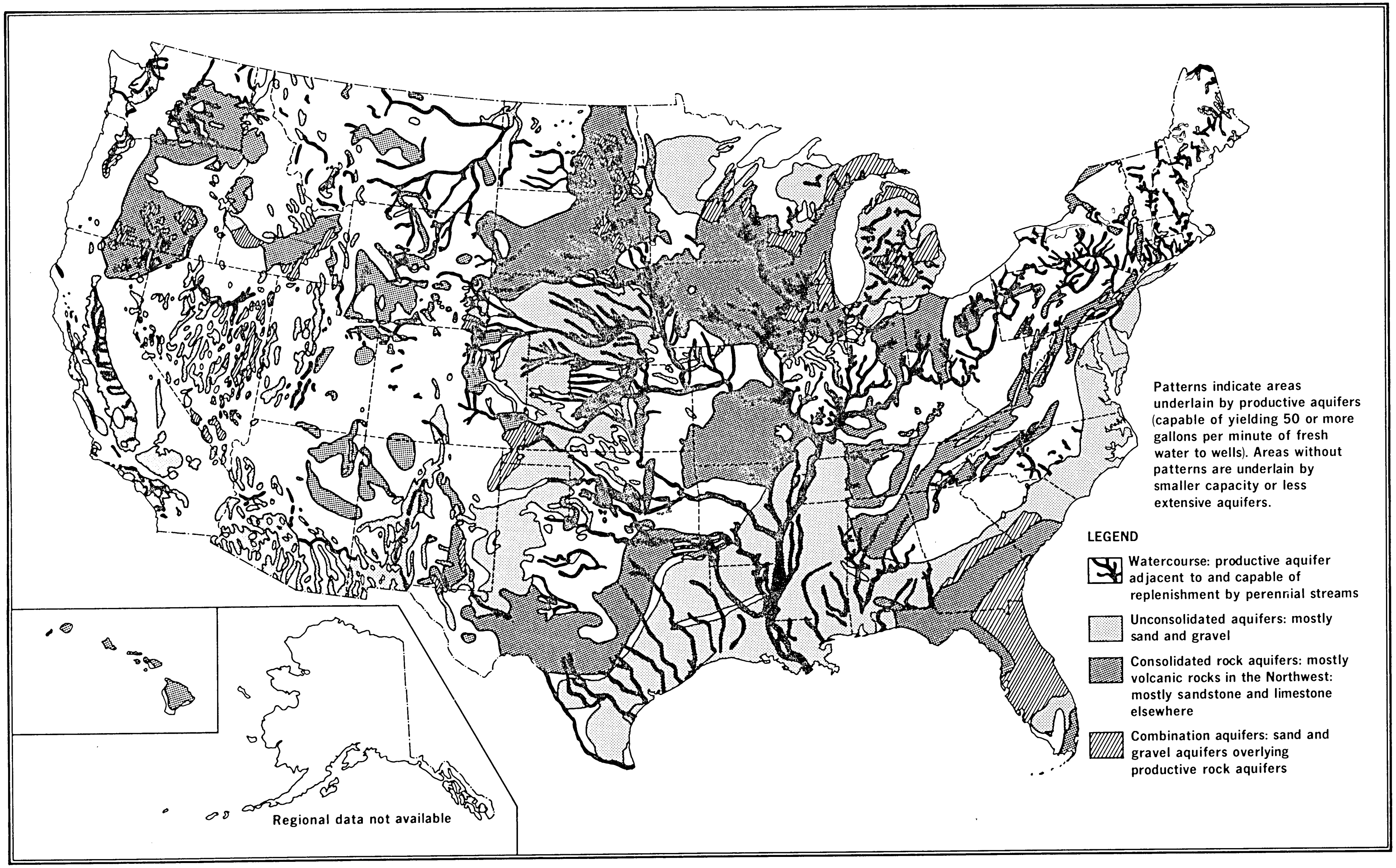


Figure 5.4. Major aquifers in the United States (U.S. Water Resources Council, 1978).

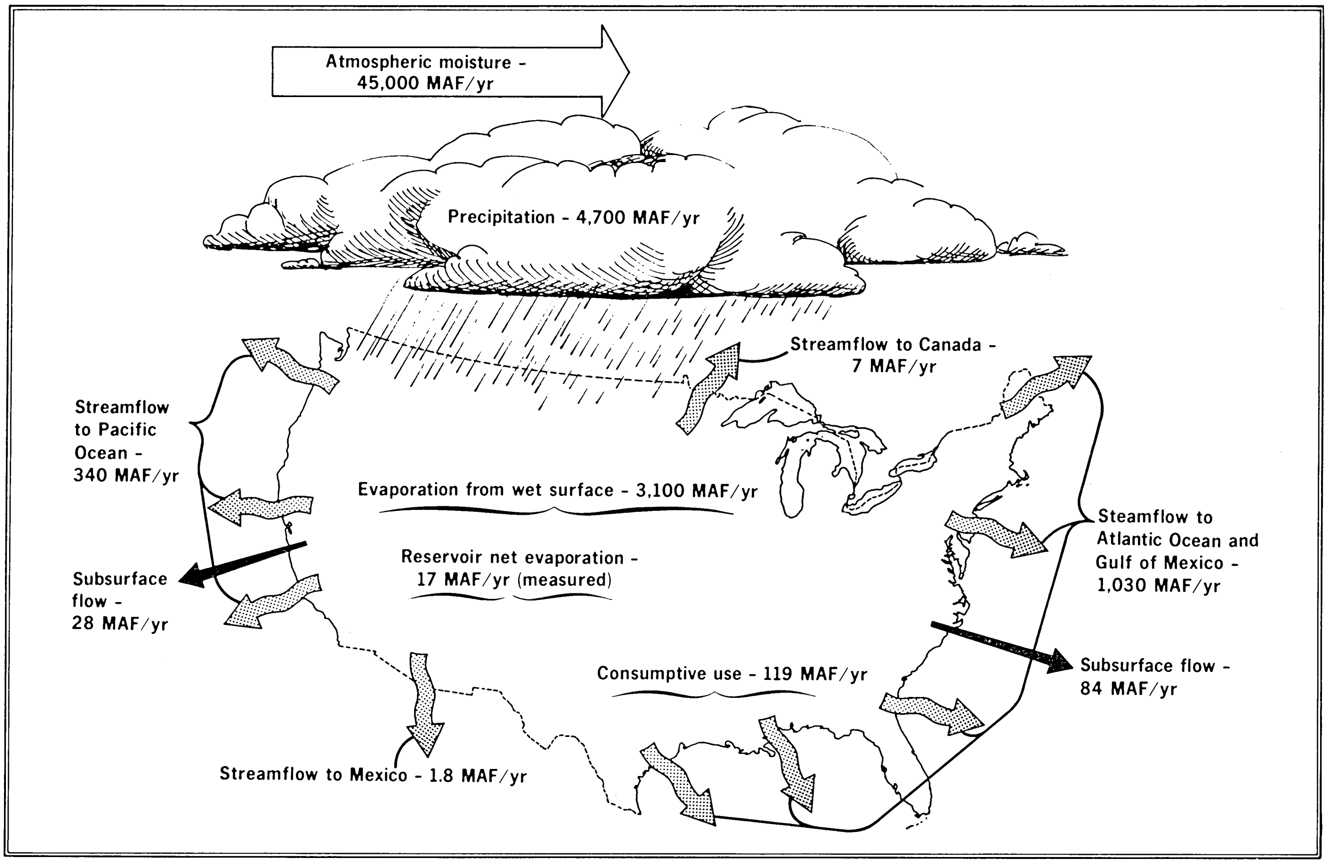


Figure 5.5. Water budget for the United States in millions of acre-feet (MAF) per year (U.S. Water Resources Council, 1978).

Irrigation Water Requirements

Crop production without irrigation is possible in semiarid areas that receive 15 to 20 inches of precipitation per year. However, in most years, crop yields without irrigation are less than potential yields with irrigation. Areas that receive 20 to 30 inches annually are subhumid and some irrigation is usually needed to obtain good crop yields. Humid areas generally receive more than 30 inches of annual precipitation. Some irrigation is needed on most soils and crops to obtain maximum yields because rainfall pattern seldom coincides with crop water needs. Irrigation is needed especially on crops grown on shallow or sandy soils with low waterholding capacities. Sandy soils in the Southeast, for example, seldom hold enough available water to supply the ET from a crop with a full canopy for more than five days. Without irrigation, significant plant water stress occurs most years on crops grown on these soils.

Water Supplies for Irrigation

Most of the water used for irrigation comes from one of three sources: (1) direct diversion or pumping from streams; (2) gravity releases from surface reservoirs located on streams; or (3) pumping from ground water aquifers. A fourth source, currently much smaller but increasing in importance, is recycled waste water from various processing plants and municipalities.

The earliest irrigators in the West diverted water from streams and used unlined earthen ditches to transport that water by gravity to fields. Small dams or barriers were built in the streams to control the amount of water diverted to the ditch. Such diversions are still in use. However, as the volume of water use increased, stream flow after the spring runoff typically was not adequate to meet all crop water requirements.

Western water law, known as the Appropriation Doctrine was established to protect the water supplies and investments of the first diverters. The Appropriation Doctrine of water rights permits lower priority users, those who began diverting water at later dates, to legally divert water only during runoff from large storms or peak periods of snow melt, or periods when little water is needed by those holding the early water rights. Thus, this water law became know as the "first in time, first in right" doctrine.

Reservoirs

Because most western stream flow rates are highly variable and because times of high flow typically do not coincide with crop water requirements, dams were constructed on many streams to accumulate runoff water in surface reservoirs for later release as required for the various beneficial uses. Large reservoirs store water during years of high runoff for use in years of low runoff and they reduce runoff to the oceans.

Dams and reservoirs are most effective when designed and used for multiple purposes. However, the requirements for water supply, flood control, power production, and recreation often call for operating policies and strategies that differ from those for irrigation water storage. For flood control, reservoirs are most effective if normally empty. Recreation interests, however, prefer a constant water level for fish reproduction, ease of operating boat launching facilities, and docks. With careful planning, reservoirs can be operated as a compromise between these various interests, allowing water levels to be drawn down toward the end of each irrigation season, refilled with spring snow melt, and left with some capacity to store unanticipated flood flows.

In the eastern United States, most reservoirs used for irrigation are small, and designed strictly to store surface runoff. Small ponds also are excavated to depths that allow them to intercept shallow ground water. In some cases, ground water may be pumped to ponds or pits.

Ground Water

Ground water began to be extensively developed for irrigation in the United States in the 1950's as a result of below normal precipitation coupled with the availability of efficient pumps and well-drilling equipment and procedures. Areas of particularly extensive ground water development include southern Georgia, eastern Arkansas, the central and southern Great Plains, central Arizona, and the central valleys of California. By the 1970's, ground water withdrawal in many areas was taking place at a rate faster than the natural recharge — "ground water mining" was occurring. The declining water table levels posed three concerns to irrigators.

1. Increasing pumping lifts and higher energy costs were rapidly increasing pumping costs.
2. The yields, or flow rates, from irrigation wells were rapidly decreasing making it difficult to irrigate efficiently and profitably.
3. The ground water resource was being depleted.

Recycled Water

In hydrologic terms, essentially all water is recycled. However, the term, recycled water, usually refers to water that has been used once for human activities and then is reclaimed and used at least one more time before evaporating or running off to the oceans. Principal sources of recycled water for irrigation are: (1) irrigation return flows; (2) municipal and industrial waste effluents; (3) agricultural feedlot runoff; and (4) food processing plant wastes. Use of recycled water is encouraged whenever possible since it extends other water supplies; however, the quality of the water relative to its intended use must be considered.

Many irrigation return flows are suitable for reuse. However, because of high concentrations of organic trash or suspended sediment, surface flows may require special treatment before the water can be used for irrigation. Municipal and industrial waste waters need to be analyzed for chemicals that might be absorbed by the plants and be toxic to human or animal consumers of irrigated crops. A major concern is with the heavy metals (for example, copper, cadmium, zinc, lead, cobalt) that are present in waste waters from certain industries and that may not be removed in treatment facilities. Municipal and industrial wastes may also contain various forms of nitrogen and phosphorus, nutrients that can be either beneficial or detrimental to many irrigated crops.

Feedlot and agricultural processing wastes are also potential sources of irrigation water. The solids they contain may not flow through small orifices in some water application systems. Settling ponds or trash removal screens can help to make these sources of water usable. Waste water may be generated during a time of year when irrigation water is not needed, so that water storage facilities must be provided to match supply with need.

Quality of Water for Irrigation

Major water quality characteristics that determine the suitability of water for irrigation are: its salt content (salinity); the composition of salts, particularly sodium and chloride; various trace elements, particularly boron; pesticide residues; various plant nutrients; and plant and animal pathogens.

Salinity is the major water quality factor for irrigation because crops vary in their tolerance to salinity. Sodium is of major concern because of its detrimental effects on the infiltration rate of soils. Once soils are affected by sodium, they are difficult to reclaim.

Quantities of Water Used for Irrigation

Crop and Irrigation Water Requirements

Factors affecting the quantity of water required by crops have been described earlier in this report. Evaporated or transpired water, which enters the atmosphere as water vapor, is not available for local reuse and is referred to as consumed water or consumptive use. The amount of water required to produce a crop (in addition to that supplied by precipitation), plus water required to leach soluble salts from the soil is called the irrigation water requirement. The Soil Conservation Service (U.S. Department of Agriculture, 1976) has estimated the average monthly and seasonal ET rates for most economically important irrigated crops in all water resource regions of the United States. The maximum irrigation requirement in the United States occurs in southern Arizona for alfalfa hay (a year-round crop), and exceeds six acre-feet per acre per year. Alfalfa yield per unit of water, however, is about the same in all areas.

Effective Use of Precipitation

In areas where irrigation water supplies are scarce or expensive, irrigators try to manage their fields to maximize use of precipitation. Usually, this requires retention of all of the precipitation where it falls by changing the microtopography of fields to prevent runoff. In some areas, the topography of higher land areas is altered, or plant composition is modified, to increase runoff to irrigation supply reservoirs. Sometimes, runoff from such areas is channeled directly to level irrigated fields surrounded by low dikes. This process is called water harvesting.

Volumes of Water Used for Irrigation

In 1985, the total volume of diversions for irrigation was 154 million acre-feet (MAF) for the nation and 140 MAF for the 17 western states. The total volume of fresh water consumed by irrigated crops was 83 MAF (Solley et al., 1988). In 1980 (Solley et al., 1983), the comparable figures were 170 MAF withdrawn for the nation and 154 withdrawn for the 17 western states. Consumption was 93 MAF for the nation and 82 MAF in the western states. The apparent decreases from 1980 to 1985 may be partly due to changes in the methodology used by the Geological Survey and cooperating states in gathering and presenting that data. Part of the difference may be due to a decrease in irrigated acreage because of changes in U.S. Department of Agriculture (USDA) programs and a decline in the farm economy. Lowered ground water levels and increased energy costs for pumping also may have reduced ground water withdrawals.

Much water diverted or pumped for irrigation is returned to natural water bodies for reuse. In the Second National Water Assessment (U.S. Water Resources Council, 1978), diverted water was defined to include that taken from streams and rivers, released from reservoirs, and pumped from ground water. In the 17 western states, 46% of the total water diverted for irrigation returned to sources where it could be reused. Considering the additional water consumptively used for beneficial purposes, only 13.2% of the total diversion was not used productively or made available for further diversion. The nonproductive uses included evaporation from canals, reservoirs, and wet lands; noncrop, water-loving plant transpiration; and recharge to ground water bodies from which the water is not easily or economically recoverable. For the nation as a whole, the percentages were essentially the same, with all but 13% of diversions not beneficially used or available for reuse.

The above data indicate that any program designed to improve irrigation practices for purposes of saving water has the potential of saving only about 13% of the water diverted for irrigation; not 59% as might be suggested by the difference between diversions and beneficial consumptive use alone.

Recoverable Return Flows

Irrigation return flows usually are reused for irrigation or other purposes when they return to stream channels above diversion points or to ground water aquifers. Water quality usually is degraded because dissolved salts have become more concentrated. Return flows usually mix with the original stream or other water bodies so that the net adverse effect on water quality from any one irrigation project may be small. If an irrigation project is underlain by geological deposits containing large amounts of salts, return flows may be much more saline because of a process called salt loading.

Return flows are not reusable for irrigation if they return to streams below the lowest diversion, or if they flow to inland saline lakes such as the Great Salt Lake or the Salton Sea. Return flows may also be lost to further economic use if they are lost by evaporation or low-value or nonbeneficial vegetation ET before they reach a usable water body or stream.

Quality of Irrigation Return Flows

In addition to increased salinity, irrigation water may have other adverse quality characteristics. Surface return flows to streams may have a higher concentration of sediments than the original diversion, depending on the type of irrigation system, the level of the irrigation management, and the erodibility of the irrigated soils. If return flow is to be used for municipal or industrial purposes, the sediments will increase the cost of water treatment.

When irrigation water returns directly to ground water, the filtration process that takes place as water moves through the soil removes most solid particles and the soil absorbs some chemicals. However, some highly soluble contaminants may be carried to the ground water. If the distance to ground water is large, the travel time for the bulk of contaminants to reach the ground water may be months or years. However, since the flow velocity through the larger soil pores may be many times larger than the average flow velocity, contaminants may be detected in ground water long before the bulk quantities arrive. If ground water tables are shallow, and soils are coarse and without restrictive layers, percolating return flows may reach the ground water in days or a few months.

The principal contaminant of deep percolating return flows from irrigated land is nitrate, a highly soluble form of nitrogen. Nitrate nitrogen exists in most irrigated soils where it has accumulated naturally from legume crops like clovers or alfalfa that fix nitrogen from the air, or from nitrogen applied as fertilizer. Some nitrate nitrogen percolating below the root zone is reduced to a gaseous form and escapes to the atmosphere. However, the degree of reduction depends on many factors and is not necessarily complete.

Nitrate nitrogen in ground water may or may not be a problem, depending on the future uses of the water. For example, if the ground water is pumped again for irrigation, nitrate may be beneficial in meeting nitrogen requirements for crops, and may reduce the irrigator's need to apply additional fertilizer. For human consumption, especially by infants, nitrate-nitrogen in drinking water can impose a health risk. The nitrate-nitrogen concentration in aquifers in a number of locations exceeds the United States Public Health Service recommended safe levels for domestic water supplies.

Pesticides are causing increasing concern as ground water contaminants. Most agricultural pesticides are either not highly soluble, or they form chemical bonds with soil particles which greatly retard their movement to the water table. Others, however, are water soluble and may move downward in solution. Numerous studies are underway to assess the magnitude of this problem and to develop management strategies to reduce ground water contamination.

In some areas, because of the slow movement to ground water, appreciable volumes of contaminated waters may be in transit between the soil root zone and the saturated zone of ground water, and thus contaminants have not yet been detected in aquifers.

Effects of Irrigation Diversions on Fisheries and Wildlife Habitat

Irrigation diversions may affect habitat for fish and for game and nongame animals. If the entire flow of a stream is diverted for irrigation, the dewatered reach below the diversion point is obviously poor habitat for fish. On the other hand, irrigation-water releases from storage reservoirs or irrigation return flows may provide good instream flow for fisheries during periods of the year when flow would be deficient under natural conditions. These effects are now being given more attention. For example, reservoirs have become sport fisheries and sites for water-related recreation activities in most regions of the U.S. where such facilities would otherwise be in short supply.

Reservoirs, irrigation canals, and drainage channels in irrigated areas are used by migratory water fowl. Irrigated fields provide good habitat for game birds such as the ringneck pheasant. Wildlife habitat is also provided by enhanced vegetation in areas where irrigation return flows have raised the water table near enough to the soil surface that ground-water supported plant growth is possible.

6. Irrigation Systems and Management

Irrigation application systems are classified into four categories based on how water is applied: (1) surface; (2) sprinkler; (3) microirrigation; and (4) subirrigation.

Surface irrigation systems distribute water on the surface of the soil by gravity. Surface irrigation systems usually require shaping the surface of the field to enable water to flow uniformly in field distribution channels. Water enters the soil from these channels. The amount applied is determined by the intake rate of the soil and the "opportunity time" that water is available at any point on the soil surface. A channel may be a furrow between crop rows, a strip of land bordered by low dikes, or the entire field may be irrigated.

Sprinkler irrigation systems discharge water through the air from sprinkler heads or spray nozzles mounted on pressurized distribution pipes. The sprinklers, and sometimes the pipes, are mounted on fixed or moving supports. The rate of application is controlled by the system. The amount applied is determined by the hours of operation.

Microirrigation systems, such as drip or trickle, distribute water in closely spaced, pressurized conduits. Water is discharged from emitters, miniature sprinklers, or porous conduits at low flow rates and low pressures. Microirrigation systems require more frequent application than do surface and sprinkler methods. The conduits and outlets are usually placed on the soil surface, but may be buried at shallow depths or attached to trees in orchards. The rate of application and amount applied are controlled by the system.

Subirrigation systems require raising the water table so that capillary action will move water upward into the soil root zone. Water is supplied to the saturated zone beneath the crop root zone through underground conduits, or where surface soils are porous, through unlined surface channels. Subirrigation systems are used only where underlying formations allow the creation and maintenance of a shallow water table.

Surface Irrigation Systems

Border strips are used to irrigate close-growing crops like small grains. Furrow irrigation is used to irrigate row crops or crops planted on raised soil beds. Both close-growing and row crops can be irrigated in level basins surrounded by low dikes. In all surface systems, water flows by gravity over the land.

Water is delivered to the upper end of each border, furrow, or basin from a head ditch or pipeline. As water advances in the field channels, part of the flow infiltrates the soil. When the water reaches the lower end of the field, some will run off the field if the downstream ends of the channels are not blocked. When sufficient water has been applied, inflow is stopped manually or by automated controls. When water recedes from the channels, irrigation of that border or group of furrows is complete. Ideally, for complete irrigations, the amount of water infiltrated will be just adequate to replace depleted soil water at the downstream end of each field channel.

It is difficult to predict the optimal flow rate and application time to exactly replenish the depleted soil water because the rate of infiltration and rate of advance of the irrigation streams over the soil surface varies from one irrigation to the next. The required time for infiltration is usually longer at the upstream than at the downstream end of each field channel. Therefore, if the downstream end is fully irrigated, more water may be infiltrated at the upstream end than the soil can hold. Water that moves beyond the root zone, called deep percolation, usually returns to the ground water aquifer and eventually back to surface water bodies.

Water should be applied to each border or group of furrows long enough to ensure an adequate irrigation. Flow rates and application times for uniform irrigations can be predicted for some well-designed systems. Most irrigators use past experience to fine tune water application times and flow rates as soil and crop conditions change during the season. However, runoff volumes are difficult to predict. Deep percolation volumes are more difficult to predict because they cannot be observed. Therefore, optimal flow rates and times settings may not be known, or are not always used. Surface runoff can be captured and returned to the same field or farm with a tailwater reuse system. Otherwise, return flows may be a source of water for downstream irrigators or other water users.

Detailed information describing operational characteristics and design procedures for surface irrigation systems can be found in many publications (Jensen, 1980; U.S. Department of Agriculture, 1974; 1983a; 1983b; 1984).

Border Systems

Border systems (Figure 6.1) are suited to all crops that are not damaged by inundation for short periods of time. They are used on nearly all irrigable soils but are best suited to soils whose infiltration rates are

Figure 6.1. View of border irrigation of a pasture. Photograph courtesy of Marvin E. Jensen, CIIM, Fort Collins, Colorado.

neither extremely low nor extremely high. Border strips range in width from 30 to 100 feet and are separated by low dikes. Field slope should be less than 3%.

Graded Furrows

Graded furrows (Figure 6.2) are formed between crop rows prior to the first irrigation. Row direction is often parallel to maximum field slope, but may be different if a lesser slope will improve the furrow flow hydraulics. The method differs from border irrigation in that only part of the soil surface is covered with water during irrigation.

Corrugations

Corrugations are small, closely spaced channels used to irrigate close-growing crops on moderately steep land. Corrugations generally have smaller capacity than furrows, and sometimes are used within graded borders to improve water distribution.

Level Basins

Level basins are similar to borders, but have no slope in any direction. They are diked on all sides, so all applied water will infiltrate. Basins are best suited for lands that are originally nearly level, so earth moving costs for leveling are not excessive. The irrigation stream must be large enough to cover the entire area in a relatively small proportion of the time required for infiltration of the desired amount of water. Since some crops are sensitive to ponded water, level basins may not be applicable for these crops unless furrows are used within the basin. This system generally is not used in humid areas where rapid surface drainage of excess rainfall may be necessary except where rice, which can tolerate ponding, is grown.

Adaptability

Surface irrigation systems are best suited for uniformly fine to medium textured soils with relatively small, uniform slopes. The major initial expense for surface irrigation systems is for reshaping the field surface — a one-time investment. If the original field slope approximates the final design slope, minimal earth moving is required to achieve the desired grade.

All crops can be irrigated with one of the several surface irrigation methods. Surface irrigation may be the most practical method where dissolved salts in irrigation water can cause damage when sprayed on crop leaves, or when disease problems may occur from wetting the vegetation with sprinklers.

New Developments in Surface Systems

Although surface irrigation systems have been used for centuries, new techniques and improved manage-

Figure 6.2. View of graded furrow system being irrigated using gated pipe. Photograph courtesy of R. S. Pollock, U.S. Department of Agriculture, Soil Conservation Service, Nebraska.

ment are continuously being developed. The adoption of laser controls to land leveling equipment in the 1970s greatly simplified and improved land reshaping and smoothing (Figure 6.3). In 1979, a technique labeled *"surge irrigation"* (patented by Utah State University Foundation, Stringham and Keller, 1979) was developed for increasing the rate of advance of water in furrows. Surge irrigation involves the intermittent releases of water into irrigation furrows. Surging furrow flow on some soils results in a more uniform infiltration opportunity time along the length of the furrow and may reduce deep percolation. Commercial water control equipment is now available to automatically achieve surge flow.

Another recent development to both automate surface irrigation systems and improve their performance is *"cablegation"* (Figure 6.4) (Kemper et al., 1981). Cablegation is achieved with a plug that moves slowly within a surface pipeline placed at the upstream end of a furrowed field. The system is automated by use of a mechanism to control the speed of the moving plug. Water is released in sequence, and at varying rates, to the furrows from openings in the pipe.

Sprinkler Irrigation Systems

Sprinkler irrigation systems are classified by how the pipe distribution systems (the laterals) are operated. Some laterals are stationary throughout the year, some are moved after each irrigation, while others move continuously while applying water. The three main types of sprinkler systems are: (1) fixed systems; (2) periodically moved systems; and (3) moving systems (U.S. Department of Agriculture, 1983b). Examples of common sprinkler systems are shown in Figure 6.5.

The pressure required to distribute water and operate sprinkler heads is usually provided by pumps. In a few locations, pressure may be provided by gravity if the elevation of the water source is high enough above the area being irrigated.

Well-designed fixed and periodically moved systems can apply water with acceptable uniformity when wind speeds are low and the application rate does not exceed the soil infiltration rate, thereby preventing runoff. Moving systems generally apply water more uniformly than periodically moved and fixed systems. The travel speed of moving systems, which controls the amount

Figure 6.3. Laser-leveling of a level basin. Top photograph courtesy of Robert C. Bjork, Agricultural Research Service, U.S. Department of Agriculture, Beltsville, Maryland. Bottom photograph courtesy of A. R. Dedrick, U.S. Water Conservation Laboratory, Phoenix, Arizona.

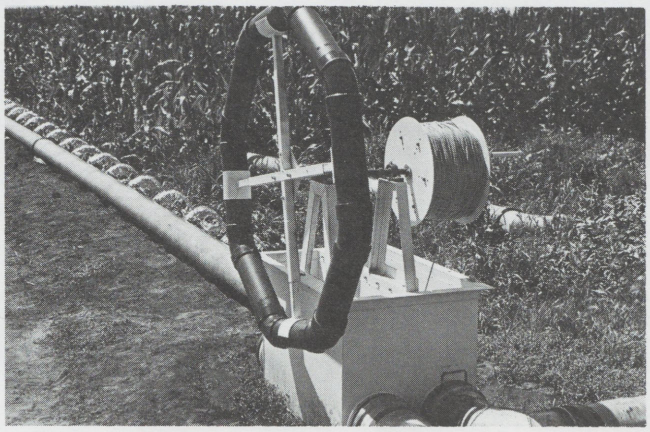


Figure 6.4. Cablegation irrigation system. Photograph courtesy of U.S. Department of Agriculture, Soil Conservation Service, Nebraska.

of water applied in a single irrigation, can be regulated by the irrigator. Design information for sprinkler systems is available from the same sources listed for surface systems.

Fixed Sprinkler Systems

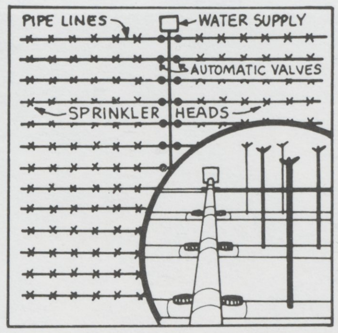
Fixed sprinkler systems do not need to be moved after installation. Sufficient lateral pipe and sprinkler heads are required to cover the entire field. To irrigate the field, the sprinklers only need to be cycled on and off by applying water under pressure at the inlet of the system. Laterals may be buried or placed on the field surface. Most fixed sprinkler systems have small sprinklers spaced 30 to 80 feet apart, but some systems use large "gun" or hydraulic type sprinklers spaced 100 to 160 feet apart.

A sprinkler system is portable if the laterals can be moved into and out of the field during the growing season to permit tillage, planting, and harvest operations.

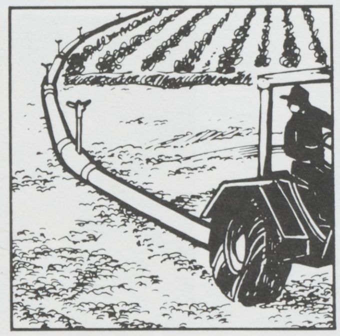
Periodically-Moved Sprinkler Systems

Periodically moved sprinkler systems are similar to fixed systems, but there are only enough laterals and sprinklers to irrigate a portion (a set) of the field at one time. The laterals and associated sprinklers must be moved from one set to another to irrigate the entire field. *Hand-move portable laterals* may be supplied with water from portable or buried mainline pipe. Laterals commonly consist of lengths of aluminum tubing that are easily coupled and uncoupled. Hand-move systems have a relatively large labor requirement.

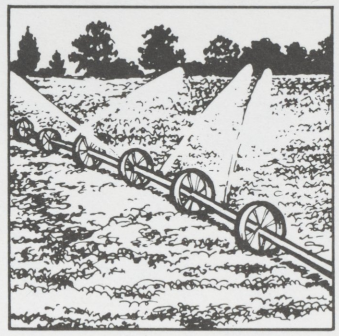
End-tow lateral systems are similar in concept to hand-move laterals except they have rigidly coupled



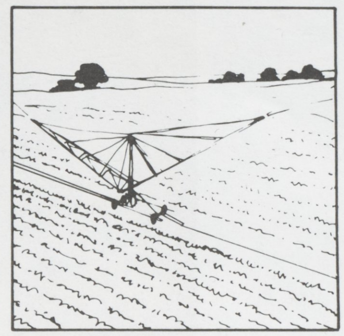
Solid Set Sprinkler



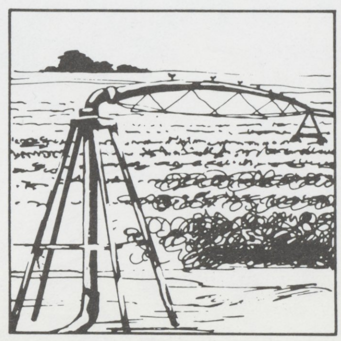
Skid Tow



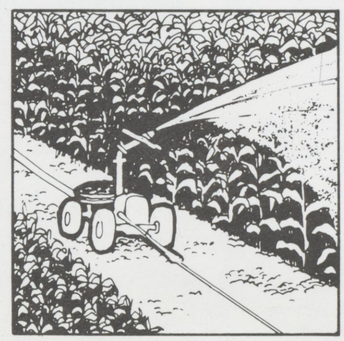
Side Roll



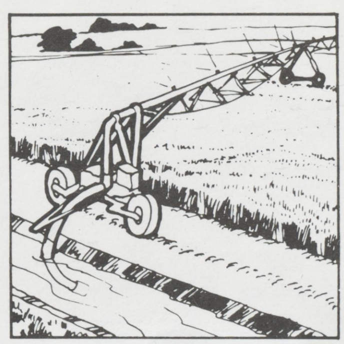
Boom Type



Center Pivot



Traveling Big Gun



Linear Move

Figure 6.5. Sketches of various types of sprinkler irrigation systems. Sketches courtesy of Agricultural Engineering Department, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln.

Figure 6.6. Aerial view of a center pivot sprinkler irrigation system. Photograph courtesy of Michael Deacon, Valmont Industries, Inc., Valley, Nebraska.

pipe sections. The laterals usually are towed from set to set with a tractor.

Side-roll laterals are a third type of periodically moved system. The lateral pipes are rigidly coupled together and each pipe section is supported by a large wheel. The lateral line forms the axle for the wheels, and when rotated, the entire line can be rolled to the next set. The unit may be moved mechanically by an engine mounted at the center of the line or by an outside power source at one end of the line.

Moving Sprinkler Systems

Moving sprinkler systems apply water to the soil while they are in motion. The *center-pivot irrigator* is the most common moving system (Figure 6.6). The lateral pipeline is fixed at one end and rotates to irrigate a large circular area. The fixed end of the lateral, called the "pivot point", is connected to the water supply. The lateral consists of a series of spans ranging in length from 90 to 250 feet. Each span is carried about 10 feet above the ground by a drive unit, an "A-frame" tower supported on wheels propelled by electric or hydraulic motors.

Mechanical devices at each tower keep the lateral in alignment. The rotational speed of the system is governed by the speed of the end-drive unit, which can be controlled by the operator. Most common center-pivot laterals are one-quarter mile long and irrigate the circular portion, about 130 acres, of a quarter section (160 acres).

The *traveling sprinkler,* or traveler, is another type of moving system. It consists of a large capacity sprinkler mounted on a self-powered chassis. The sprinkler travels in a straight line while being supplied with water through a flexible hose (Figure 6.7). Some traveling sprinklers move parallel to open ditches, from which water is lifted and pressurized by a pumping plant mounted on the chassis. Travelers usually operate at high pressures and have high energy requirements.

Self-propelled, *lateral-move systems* combine the structure and guidance of a center-pivot lateral with a water feed system similar to that of a traveling sprinkler. They operate at lower pressures than travelers. Lateral-move systems move continuously in a direction perpendicular to the lateral. For effective operation, they require rectangular fields free from obstructions.

A modification of the lateral-move and pivot systems has been developed by Lyle and Bordovsky (1981). Their *low-energy, precision application (LEPA)* system uses low pressure water emitters discharging just above the soil surface. When used in conjunction with modified tillage practices, including closely spaced dikes in furrows, LEPA systems use both irrigation water and rainfall effectively.

Adaptability

Sprinkler irrigation systems are suitable for most crops and are adaptable to most irrigable soils. This flexibility is possible because sprinkler heads are available in a wide range of discharge capacities. A well-designed system applies water at a rate that is less than the soil's infiltration rate. Design involves the selection of proper nozzle size, operating pressure, and sprinkler spacing to apply water uniformly at the

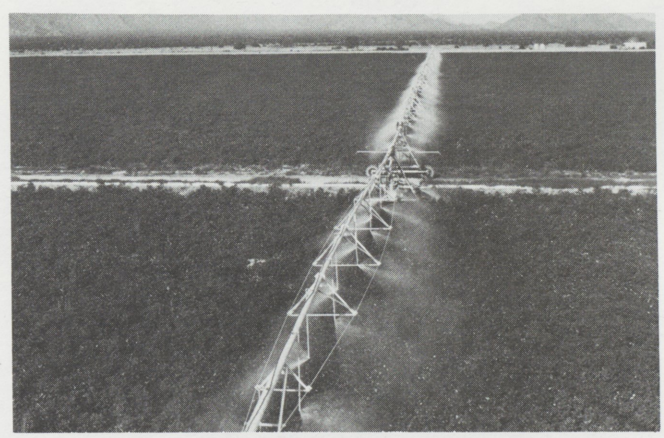


Figure 6.7. Lateral-move sprinkler irrigation system. Photograph courtesy of U.S. Department of Agriculture, Soil Conservation Service, Nebraska.

design rate. The effects of wind can greatly decrease irrigation uniformity and must be considered in the design.

Periodically moved systems are used where irrigations are not required more often than every five to seven days. Fixed or continuously moving systems are better-suited for conditions where light, frequent irrigations are required such as for shallow-rooted crops or for soils with low water-holding capacities. Fixed systems also can be designed and operated to provide frost and freeze protection, blossom delay, and crop cooling. The flexibility of sprinkler equipment and its ability to control application rates make sprinkler systems suitable for most topographic conditions.

Spray Evaporation Losses

Since sprinkler irrigation systems discharge water into the air above the crop canopy, some evaporation occurs from the water droplets. Under windy conditions, small droplets may drift outside the targeted area of application. The amounts of evaporation and spray drift are difficult to measure accurately. Most measurements have shown spray evaporation and drift to range from 5 to 20% of the water discharged.

Evaporation also occurs from the crop canopy and the soil surface wetted by sprinklers. Usually, evaporation from wet surfaces causes a corresponding decrease in the transpiration that would otherwise occur. Frequent, light irrigations tend to result in more evaporation than less frequent, heavy irrigations.

Water Quality Requirements

Sprinkler systems require cleaner water than most surface systems. Sediment and debris must be removed from the water as it can damage sprinkler systems and can plug sprinkler heads or nozzles.

Evaporation from wet foliage may cause plant damage if the irrigation water contains a high concentration of dissolved salts. Grapes, citrus, and most tree crops are sensitive to relatively low concentrations of sodium and chloride. Some fruits such as apples and cherries may be damaged by salt deposits on the fruit. Where these potential problems exist, only under-tree sprinklers may be suitable. The increased humidity and decreased air temperature within the plant canopy caused by sprinkler systems may increase incidence of diseases for some crops.

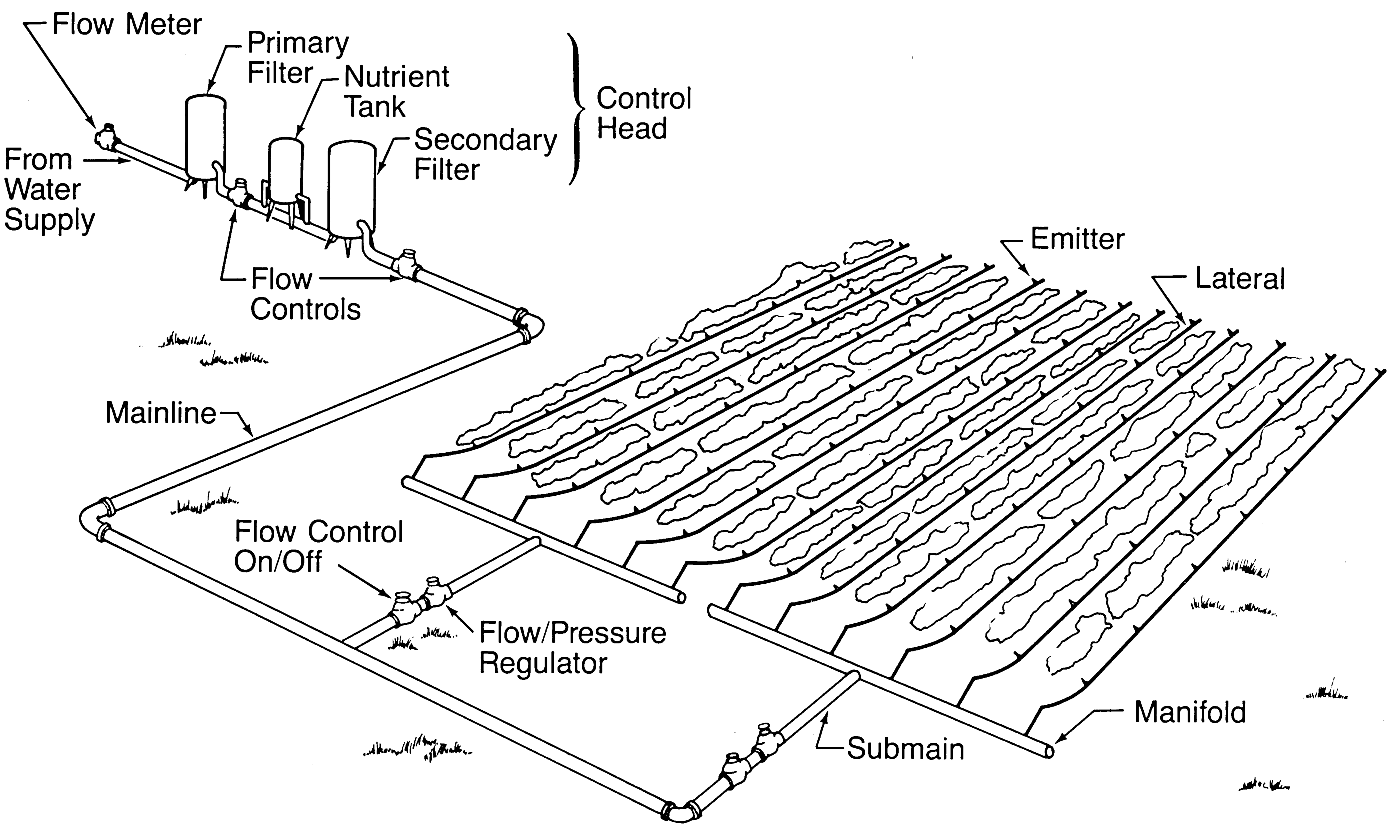


Figure 6.8. Basic units of a trickle (or drip) irrigation system. Adapted from Turner and Anderson, 1980.

Microirrigation Systems

The term "microirrigation" applies to several low pressure systems, including *drip/trickle, subsurface, bubbler,* and *miniature spray irrigation.* Basic components of a microirrigation system are shown in Figure 6.8. Microirrigation systems apply water frequently and at low rates on or beneath the soil surface. Water is applied as drops, tiny streams, or miniature sprays through closely spaced emitters attached to water delivery lines or through miniature spray nozzles.

Drip Trickle Irrigation

Trickle irrigation is the most common microirrigation system. It is best-suited for widely spaced crops (trees or vines) or high cash-value row crops. The emitters of a trickle system serve two main functions: (1) they dissipate the water pressure in the distribution system by means of orifices, vortexes or long-flow paths; and (2) they discharge a limited, nearly constant flow rate whether located in high- or low-pressure positions. Since each emitter is a point source, the soil volume irrigated by each emitter is influenced by the horizontal movement of water through the soil. The design of the system must take into account the soil volume that can be wetted, the application rate and volume of application required to replace water used by the crop, the crop's root pattern, and the infiltration and water-holding characteristics of the soil.

When the tubing and emitters are placed below the soil surface, the system is called a *subsurface irrigation system.* Subsurface irrigation is not the same as subirrigation in which the root zone is irrigated by water table control.

Usually, a higher level of design, management and maintenance is required for trickle systems than for other irrigation methods (Bucks et al., 1983).

Bubbler Irrigation System

A bubbler irrigation system discharges small streams of water to pools on the soil surface, usually around trees. The outlets and discharge rates are larger than the emitters and flow rates used with trickle or subsurface irrigation. Since the application rates normally exceed the soil's infiltration rates, small basins are required to retain the water until infiltrated.

Microspray Irrigation System

Miniature sprinklers apply water as a small spray or mist. They are used mainly for orchard and citrus crops. The water delivery system is similar to that used with trickle irrigation systems.

Adaptability

Microirrigation systems are adaptable to most crops. However, because of their relatively high initial cost they are used mainly where: (1) water is scarce or expensive; (2) soils are sandy, rocky, or difficult to level; or (3) high-value crops that require a high degree of soil water control are produced. Microirrigation systems have several potential advantages over other forms of irrigation.

1. Water is applied at low rates, enhancing water penetration into problem soils.
2. Small areas are wetted, reducing evaporation from the soil.
3. Less water is required by microirrigation systems when trees or other widely spaced plants are young than with surface or sprinkler methods.
4. Weed growth is reduced on portions of the soil surface that aren't wetted.
5. Frequent, light water applications can maintain soil water within a narrow range, which may enhance growth and yield of some crops.
6. Frequent or daily water applications maintain a dilute salt concentration in the soil water, and salts are moved to the outer limits of the wetting pattern, enabling the use of more saline water than is possible with other methods.

Disadvantages

All systems have some disadvantages, but microirrigation methods have some unique, potential drawbacks. Emitter clogging is the most serious. Clogging adversely affects the rate and uniformity of water application, increases maintenance costs, and results in decreased crop yield if not detected and corrected. Preventive measures include water filtration, chemical water treatment, periodic flushing of trickle lines, and field inspection.

Other potential problems include salt accumulation near plants, restricted soil water distribution and plant root development, and high costs.

Subirrigation Systems

In humid regions, drainage facilities are essential to enable farming some of the nation's most productive soils. Drainage is needed to provide trafficable conditions for seedbed preparation and planting in the spring and to ensure a suitable environment for plant growth during the growing season. Excessive drainage may remove water needed by the crop later in the season and may increase leaching of plant nutrients from the soil. Where surface and subsurface conditions permit, systems can be designed and managed to perform both drainage and irrigation functions. The components of a water table management system may include a combination of open ditches and subsurface tile drains. These water table management systems regulate the drainage outlet to prevent over-drainage. Water can be added to raise the water table to supply water to the root zone. During periods of heavy rainfall, the drainage outlet level can be lowered for rapid drainage to reduce the risk of crop damage. Combination subirrigation drainage systems may be economically feasible for certain soils where separate irrigation and drainage systems would not be economical.

Adaptability

Water table management systems are best suited to fields having slopes of less than 2%. A natural, impermeable barrier must exist under surface soils at depths of less than 10 feet. These conditions commonly occur in humid and subhumid areas, where periods of excessive and deficit soil water may occur within the same cropping season.

Currently, combined subirrigation-drainage systems are used primarily in the Midwest states, along the Atlantic Coast from North Carolina to Florida, and in the lower Mississippi delta.

The amount of water required with well-designed and managed water table management systems is about the same as for sprinkler irrigation systems, but water table management systems generally require less energy since the water is not applied under pressure.

Table 6.1. Labor requirements and capital costs for the various irrigation methods[a]

System	Labor requirement (h/acre-irrigation)	Capital costs[b] ($/acre)
Surface		
Border	0.2 - 1.0	120 - 400
Furrow	0.4 - 1.2	160 - 500
Corrugation	0.4 - 1.2	100 - 200
Level basin	0.1 - 0.5	200 - 500
Sprinkler		
Fixed		
Solid set portable	0.2 - 0.5	400 - 1200
Permanent	0.05 - 0.1	400 - 1200
Periodic-move		
Hand move	0.5 - 1.5	100 - 300
End tow	0.2 - 0.5	180 - 350
Side roll	0.2 - 0.7	180 - 350
Moving		
Traveler	0.2 - 0.7	200 - 400
Center-pivot	0.05 - 0.15	200 - 400
Linear move	0.05 - 0.15	300 - 500
Micro		
Drip	0.15	250 - 1000
Subsurface	0.15	250 - 1000
Bubbler	0.15	250 - 1000
Spray	0.15	250 - 1000

[a]Modified from Turner and Anderson (1980) and Lord et al. (1981).
[b]Excluding cost of water supply, pump, or power unit.

Comparison of Irrigation Systems

Design

Ideally, an irrigation system is designed to apply a predetermined amount of water so that each part of the irrigated area receives the same application depth. Unfortunately, no irrigation system is able to apply water with perfect uniformity. A major effort in irrigation system design is to optimize uniformity of water application. In surface irrigation design for uniform soils, limits on flow rates or furrow length are set so that nonuniformity will not be excessive. Hydraulic limitations on pipe networks for sprinkler or trickle irrigation are similarly determined.

Water Requirements

There is little difference in water consumed by most crops irrigated with any well-designed and managed irrigation system. However, there can be large differences in the amounts of deep percolation and surface runoff.

Advantages and Disadvantages

Each irrigation system has advantages and disadvantages. Generally, any of the major irrigation methods can be adapted for use on any irrigated crop. The primary restrictions for surface irrigation methods are slope, soil uniformity, and topography limitations. On level lands, any system can be used. As land slope increases and soils become less uniform, only sprinkler and microirrigation systems are practical. Water distribution is controlled by the pipe networks of those systems, rather than by the soil. The potential water application uniformity and the quantity and quality of the available water supply also influence the choice of irrigation method.

The final considerations in selecting an irrigation system involve capital and operating costs, crop(s) to be irrigated, and expected crop yield and quality. Ranges of installed capital costs for the various types of irrigation systems are given in Table 6.1. The increase in crop returns over the useful life of a system must be great enough to repay the capital and annual operating costs. Labor and energy are the two major components of operating costs.

Labor requirements for irrigation systems vary greatly. Automated systems, such as automated microirrigation and center-pivot systems have relatively low labor requirements. Labor requirements for the main irrigation methods tabulated by Turner and Anderson (1980) and Lord et. al. (1981) are given in Table 6.1.

The data presented in Table 6.1 do not show annualized costs because of the wide range in the expected life of the various systems or system components. The data do show the large differences in capital costs encountered because of differences in water sources, field shapes and topography, soils, and large differences in labor requirements because of automation.

7. Irrigation Water Management Technology

Management Objectives

Irrigation water management involves determining when to irrigate, the amount of water to apply at each irrigation and during each stage of plant growth, and operating and maintaining the irrigation system. The main management objective is to manage the production system for profit without compromising the environment. A major management activity involves irrigation scheduling or determining when and how much water to apply.

Many methods for determining when to irrigate and the amount to apply have been developed and field tested. Some methods require instruments for sensing soil or plant parameters that indicate soil water deficit or plant water stress. Others use mathematical models for estimating the day-to-day changes in soil water by individual irrigated fields. Inputs for these models usually involve current weather data and crop information.

Most irrigation water management concepts include some form of salinity control. The need for salinity control is of particular importance in areas where annual rainfall is not adequate to maintain an acceptable salt balance as in the arid parts of the western states.

Irrigation Scheduling

Irrigation scheduling, an essential component of irrigation management, is predicting when to irrigate and how much water to apply to meet crop needs, management objectives, and goals of the grower. Irrigation scheduling also requires adjusting target irrigation times as limited by the capacity of the irrigation system to replenish the soil water and by the need to complete other necessary cultural operations.

The important decisions of determining when to irrigate and the amount to apply are not necessarily independent of each other. These decisions are made almost daily during the growing season. The timing decision may need to be made one day to as much as a week in advance to enable the grower to order irrigation water depending on the source of water. It also may be necessary to reset irrigation pipe, arrange and complete other field operations (apply chemicals, field tillage for weed control), and arrange for the labor to irrigate the field.

Irrigation Scheduling Methods

Three methods of irrigation scheduling are based on: (1) allowable soil water depletion; (2) allowable soil water tension; and (3) allowable plant water stress. Allowable soil water depletion methods involve irrigating before soil water has been depleted below a lower limit. The limit varies with each crop, stage of growth, soil type, and climate. The net amount to be applied at the next irrigation is the amount that has been depleted, except where reserve soil water capacity is maintained for retaining rainfall that may occur after an irrigation.

The allowable soil water tension method involves irrigating before the soil water tension at one or more depths in the root zone, or averaged over the root zone, reaches a predetermined limit. The limits vary in the same manner as the allowable soil water depletion limits. The amount to be applied at the next irrigation is based on the relationship between soil water tension and depletion.

The allowable plant water stress method involves irrigating before the plant water stress in some part of the plant reaches a limit as indicated by one of several measurement techniques. The plant water stress method only indicates that an irrigation is needed and not the amount to be applied.

Allowable Soil Water Depletion Methods

Two allowable depletion methods of irrigation scheduling are widely used: (1) a computational water balance method; and (2) a measurement set-point control method. The computational method uses a water balance equation to estimate the current soil water depletion, to predict future depletions, and to predict the date when the target depletion level will occur. The set-point method involves measuring the soil water content at one or more levels in the root zone. The soil water content can be measured from soil samples or by using a neutron probe or estimated using soil moisture blocks. When using a neutron probe, the probe should be calibrated for each soil, and access tubes must be installed to allow the probe to be moved from point to point within the soil profile and from site to site within the field. Trends in the measured water content can be used to estimate when the target depletion level will be reached. Generally, the set-point method enables determining when to irrigate rather than how much to apply.

Water balance irrigation scheduling methods require other inputs such as effective precipitation (precipitation minus surface runoff and deep percolation) and actual irrigation amounts. Since inputs are difficult to determine accurately, periodic measurements of soil water depletion are used to adjust the model to existing conditions or to fine-tune model components. With reliable field and crop data the essential predictions usually are sufficiently accurate for practical purposes. When used on individual fields and crops year after year, the soil water balance models can be calibrated to provide accurate estimates of soil water depletion and irrigation schedules. An example of an allowable depletion scheduling method is the USDA/ARS computer program IRRIGATE (Jensen et al., 1970; Jensen et al., 1971).

In areas that have predictable desert-like climate such as in parts of California, a water balance method based on historical average data can be used to preprogram likely irrigation dates and amounts for the season before crops are established (Fereres, 1981).

Other Scheduling Inputs

Effective Precipitation

Precipitation that moves below the crop root zone as deep percolation and/or that leaves the field as surface runoff is not effective. For example, rainfall immediately after an irrigation may not be effective because of deep percolation and/or runoff. Similarly, high intensity rainfall that produces runoff reduces rainfall effectiveness. Rainfall after a crop has matured will not be effective for the current crop, but if stored in the root zone it may be effective for a crop during the next growing season.

Water From Shallow Ground Water

Depending on the depth of the ground water and its quality, most crops can extract some water from the capillary fringe above the water table. The amount extracted reduces the rate at which available soil water is depleted from the root zone. The contribution of water from the water table is influenced by the depth of the water table below the root zone, the hydraulic properties of the soil profile, and the soil water content within the root zone. For fine-textured soils such as clays, water can move several feet upward toward the root zone, but the rate of movement is relatively low. Conversely, for coarse textured soils, the distance of upward flow is relatively small, but the rate can be relatively high. In areas where salinity is a problem, upward flow also brings salts into the root zone which must be leached.

Stored Soil Water

The water stored in the root zone at the beginning of the growing season from off-season precipitation, or left over from the previous irrigation season, is needed to begin calculations. If irrigation water has been applied throughout the season and the end of the season soil water content level is relatively high, there will be little storage capacity left in the root zone so that the contribution of off-season precipitation to soil water will be small.

Allowable Soil Water Tension and Plant Stress Methods

Soil-based Measurements

After establishing the crop, sensors are used to measure soil water tension at specific depths in the root zone. The sensors are placed in the soil with electrical lead wires or a pressure gauge at the surface. Several series of sensors are usually needed to measure soil water tension at different depths within the root zone and in several locations in the field. They can be used with an automated irrigation control system to initiate irrigations and to provide feedback to controllers.

The most widely used sensors are tensiometers. Since tensiometers are able to measure tension over a narrow range, they are most useful in the wetter ranges of fine-textured soils (clays and clay loams) and on coarser-textured soils (sands or sandy loams), which release most of the available water within the tensiometer range.

Plant-based Measurements

Plant-based measurements generally are more complex to make than soil-based measurements and are used mainly by researchers or technicians. An exception is the infrared thermometer (IRT) for monitoring crop foliage temperature relative to air temperature. The difference between the crop foliage and ambient air temperatures is related to the water status of the crop (see expanded discussion under emerging technologies). The use of an IRT for measuring the foliage temperature of a field is shown in Figure 7.1.

Figure 7.1. Steve Carl, CCT Corporation, uses the Scheduler[R] Plant Stress Monitor to measure and assess plant water stress.

Visual observations of the crop often indicate plant water stress. However, most of these indications are only visible after plants have experienced a soil water deficit that may already have reduced crop yield and/or quality. Aerial photography with both visible and near-infrared wavebands is being used more widely to support irrigation scheduling services by helping to identify soil water deficits and other stress factors in the crop. It also is used to evaluate irrigation system performances (over- or underirrigation in surface irrigation, plugged sprinklers or emitters, and other system problems).

Consulting Services

In most major agricultural regions, private agricultural consultants now offer services such as monitoring insect populations and plant nutrient levels, evaluating irrigation system performance, irrigation system design and irrigation scheduling. Many irrigation scheduling consultants routinely provide periodic updates of individual field water status based on field sampling and/or water balance calculations. This information is then summarized and returned to the client who always makes the irrigation decisons. Generally, year-end summaries are provided to the client along with recommendations for the following year. The cost for these services varies widely depending on the services provided. Irrigation design and management services are also provided by some local, state, and federal agencies.

Irrigation System Effects on Management

Surface irrigation systems generally require the least capital investment for installation, depending on land leveling requirements, and often have the least operating costs, but they often require large water flow rates and may have higher labor requirements than other methods. Accurate water measurements, or controlled volume deliveries are required to achieve management objectives. In projects where water is delivered to the farm by an organization, water measurement is especially important.

The design of a surface irrigation system can simplify management decisions and operation practices. For instance, a tailwater recovery system that stores water from a previous irrigation set can be used to increase the initial size of the furrow streams in the the next set. This increases the rate of advance of water down the field and the irrigation uniformity. After the advance phase, the supplemental flow from the tailwater system is turned off which reduces the stream size and surface runoff from the lower end.

Management of microirrigation systems is quite different from sprinkler and surface irrigation methods where relatively large, infrequent applications are normally applied. With microirrigation, estimates of daily ET rates are required to determine the daily amount of water to apply unless soil water sensors are used to monitor the soil water content, or the system is automated and controlled by sensors (Howell et al., 1986). Also, because of the potential clogging of emitters and resulting effects on system performance, increased attention must be placed on routine system operation and maintenance. However, many microirrigation users report that labor for system operation can be reduced because the microirrigation system can be fully automated.

Subirrigation has been used for decades, but is expanding in areas where soil drainage is required and where a drainage system may already exist. Currently, water table control is done manually. Automatic controls are expected in the near future.

Many comparisons of irrigation methods have been made (Kruse et al., 1987; Turner and Anderson, 1980). Valid comparisons require that all systems have been designed and operated properly. Information on design and management of irrigation systems is available in publications from professional societies such as the American Society of Agricultural Engineers or the Irrigation and Drainage Division of The American Society of Civil Engineers, and from trade associations such as the Irrigation Association as well as the USDA Soil Conservation Service.

Emerging Technologies for Effective Use of Water

Emerging technologies can be grouped into several categories: physical components, management components such as irrigation scheduling, multifunction irrigation systems, and plant modifications for more effective use of water. While these are not necessarily mutually exclusive categories, they do provide conceptual distinctions that make it easier to understand the kinds of changes occurring in irrigation technology.

Physical Components

Those items making up the hardware of the irrigation system, or modifications of the land surface or soil profile are physical components.

Surface Systems

Recent surface irrigation innovations include surge-flow systems, cablegation, and laser-controlled land leveling. Advantages include more uniform water application, less erosion, and less water applied to meet crop needs. Restraints relate to topography, system design, and costs.

Sprinkler Systems

The low energy precision applicator (LEPA) system is one of the most recent developments in sprinkler irrigation hardware. The application amount and distribution uniformity of gravity and sprinkler irrigation systems are affected by many variables. These include the soil infiltration rate, soil nonhomogeneity within a field, length of run, topography, and wind speed. The LEPA system was designed to be relatively insensitive to these variables and to minimize water losses associated with them. Low energy use was also an objective in the LEPA design. Center pivot and lateral-move systems in the LEPA configuration are designed for operating pressures of between 4 and 10 pounds per square inch at the outer end. Precise control of water application is achieved by applying water directly to microbasins, at very low pressure, through drop tubes and orifice-controlled emitters, or spray nozzles.

The LEPA system was designed primarily for windy, semiarid climates where sprinkler irrigation spray drift and evaporation losses are significant, where winds distort the application patterns, and where efficient use of rainfall is a management objective. However, the energy savings aspect of low pressure make the use of such systems attractive in humid areas also. Advantages of the LEPA system include very uniform water application and, with appropriate land surface practices, no surface runoff, resulting in higher crop yields per unit of water pumped. The system has not been evaluated on or adapted to slopes greater than about 5%.

Multifunction Irrigation Systems

Multifunction irrigation systems allow the application of water and other liquid solutions or suspensions. These include agricultural chemicals, such as herbicides, insecticides, growth regulators, and fertilizers, and most recently, the application of seeds. A new approach being tested is to have two sets of nozzles, one for both water and chemicals and the other exclusively for chemical application. Multifunction systems are most easily adapted to lateral-move and center pivot systems. The systems must enable the uniform application of water without surface flow and ponding because chemicals and seeds must be distributed uniformly.

Irrigation Scheduling

Automated Weather Data Collection

One example of technology for improving irrigation scheduling is the Automated Weather Data Network (AWDN). The AWDN automatically collects hourly weather measurements. One weather station (part of the University of Nebraska's network of over 50 stations in a six state midwest region) is shown in Figure 7.2. The weather information is processed with microcomputers and disseminated in near-real time to farmers and farm consultants.

The AWDN has greatly increased the availability of reliable and useful near-real time weather data which helps users make decisions in a timely manner. Anyone with "dial-up" capability (a terminal or microcomputer with modem) can communicate with the AWDN public access system.

New technologies also are being used by consulting firms to transfer information on the current soil water status and the predicted irrigation dates to farmers.

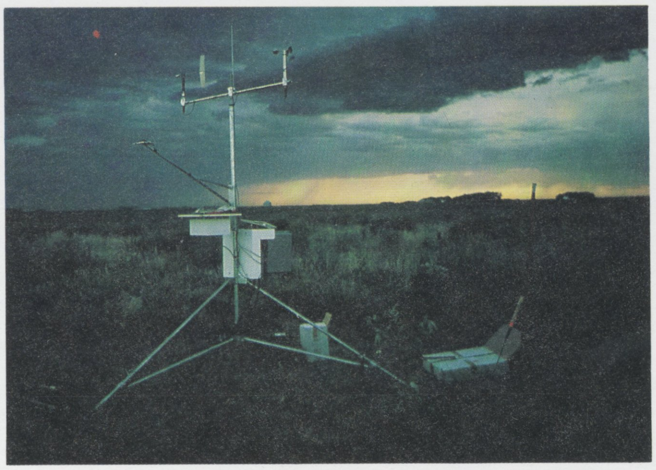


Figure 7.2. Automated weather station used to collect weather data for use in scheduling irrigations and other farming operations. Photograph courtesy of Dr. K. G. Hubbard, High Plains Regional Climate Center, University of Nebraska, Lincoln.

One consultant uses a computerized voice synthesizer that tells the farmer the current status of soil water and when and how much to irrigate each of the fields. The irrigators access the computer at their convenience using a touch-tone telephone and obtain the information that has been updated within the last few hours. This technique has reduced the cost of communications for the scheduling service (Irrigation Journal, 1987).

Remotely-sensed Crop Temperature

Recent research has demonstrated the feasibility of using canopy temperature measurements to indicate when crops begin to experience water stress, thereby signaling that an irrigation is needed immediately. There are basically two different approaches for using canopy temperature measurements as an indicator of plant water stress. The first, and most popular, called the Crop Water Stress Index (CWSI), utilizes the difference between the canopy temperature and the air temperature as a function of the humidity of the air. This approach has been successfully tested for scheduling irrigations on several crops (Geiser et al., 1982), and commercial instruments are now available to permit using this technique to schedule irrigations where water is available on demand.

The second approach is still in the developmental stage. It looks at the range or variability of several canopy temperature measurements made in the field (Clawson and Blad, 1982). Due to soil heterogeneity and nonuniform water applications, some plants begin to experience water stress earlier than others. When this occurs the canopy temperature range or variability increases and can be used to signal the need for irrigation. This approach may be well adapted for using surface temperature data collected with airplane or satellite-borne remote sensors.

Plant Modification

Recent research suggests that it may be possible to enhance the ability of plants to respond to specific environments by altering plant architecture with biogenetic engineering. It has been shown, for example, that plant hairs are an adaptive feature of plant architecture found in naturally-occuring plants growing in high solar radiation, high temperature, and low moisture environments (Ehleringer and Bjorkman, 1978; Ehleringer and Mooney, 1978). Recently soybean varieties that vary only in terms of hair type and density have been developed. Baldocchi et al. (1983) and Specht and Williams (1985) suggest that increasing the density of hairs on soybean leaves and stems might result in plants that can survive and be productive in subhumid and semiarid regions. Further research and development are needed to establish its potential application to irrigated agriculture.

8. Effects of Institutions on Water Use

Institutions involved in allocating and delivering water for irrigation can influence the effectiveness of water use in irrigated agriculture. The following brief analysis identifies alternative strategies and approaches to consider in implementing institutional changes for more effective use of irrigation water.

Definitions and Concepts

Activities of water users and suppliers can be coordinated through "institutional arrangements" (Fox, 1976). This term refers to an interrelated set of "organizations" and "rules" which enable coordinating activities to achieve social goals. "Organizations" may represent interests in the political system or groups assigned specific responsibilities for enforcing rules and for operating and managing systems that supply water. Organizations of concern could be water conservancy districts or local, state, or federal agencies. "Rules" can be statutes, regulations, or social customs. Laws governing rights to use water (water rights) or the price of water to users are the major rules of interest.

An "institutional issue" arises when there is an opportunity to make (via institutional change) progress toward social goals under existing or anticipated technical and economic conditions.

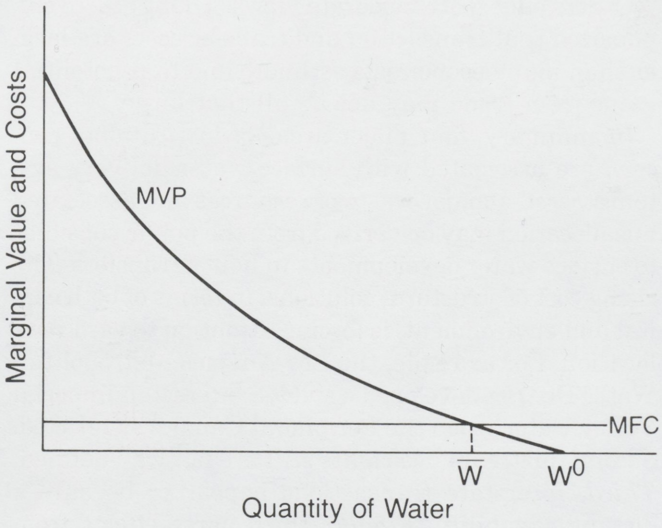


Figure 8.1. Marginal value product (MVP) versus marginal factor cost (MFC).

A social goal highly relevant to this report is economic efficiency (maximum of net value productivity for the resource base and level of technology). In addition, management rules should be fair, in the sense that equals are treated in equal fashion. Public participation and local control also play important roles in shaping water management institutions. Organization and rules are needed for orderly conflict resolution processes (Maass and Anderson, 1978).

Institutional arrangements can affect water use and profits. Institutional issues develop from the public interest in optimal resource allocation. Particularly, many institutional issues arise because of real or perceived existing, or potential, misallocation of resources from an economic efficiency viewpoint. Consequently, institutional changes may provide opportunities to improve net social welfare.

Sources and Types of Institutional Failure

Market Limitations

For a self-interested private producer, irrigation water will be optimally allocated if the marginal value product (MVP_w) is equal to the marginal factor cost (MFC_w) where the subscript w represents water, or $MVP_w = MFC_w$. The point of optimal allocation is illustrated in Figure 8.1, where the optimal use is $\overline{w}$. Where water is not priced at the margin, the irrigator will choose w^0. In addition to the economic waste implied, the excess amount may contribute to a rising ground water table, eventually leading to waterlogging.

From society's viewpoint, even though producers may be optimizing their operations within the local framework of input and output markets and within existing institutions and technology, the resources may not be efficiently allocated (Randall, 1983). Misallocations may arise from the following conditions:

1. The price (cost) of water to the irrigator may not fully reflect supply cost or social opportunity cost (the social opportunity cost representing foregone value in the best alternative use).
2. Uncompensated spillover or external costs or benefits (both technical and financial) may be present. (See also Chapter 4).
3. Product price may not accurately reflect social value of output.

4. Optimal technology may not be achieved.

Any one of the above factors can evolve into an institutional problem. The significance of the problem is related to the size of the implied misallocation.

Misallocations can be classified in different ways. First, problems can be classified by *source* of water, whether from surface supply and delivery (gravity) systems, from ground water, or from both sources. Problems also depend on the *viewpoint* or accounting stance (Howe, 1971). Private and public perspectives often differ, and the public perspective may be divided into local, state, regional, and national viewpoints. For example, a problem may exist from the national perspective while not being of significance at the state or district level, or vice versa. Potential institutional issues should be characterized as to whether the *rules or the organizations* are the focus of the problem.

Surface Water Delivery Systems

With surface water delivery systems, misallocations can arise as a result of specific public policies. For example, market transfers between and among users may be prohibited, such that the opportunity cost in alternative uses may not be signaling relative scarcities. Several types of water transactions and institutional transactions can occur with surface water delivery systems (Young, 1986), as summarized below.

Transactions Within Agriculture - Within an Organization

This type of transaction occurs frequently, usually on an informal basis. Transactions, transport, and third party costs tend to be low. However, there has been little systematic study of these transactions.

Transactions Within Agriculture - Between Organizations

Transactions of this type have larger potential for third party effects (return flows), so regulatory oversight is more likely.

Transactions Between Agriculture and Other Sectors (Off-stream)

Transactions between agriculture and municipal and industrial users are likely to have larger differences between marginal values in the competing uses. For example, where urban areas are expanding onto agricultural lands, transactions and transfer costs are low and transfers take place smoothly. More distant transactions encounter greater barriers.

Transactions Between Agriculture and Instream Uses

Hydropower and recreational uses are producing increasingly significant economic benefits. These values generally are not as yet adequately reflected in water resource allocations.

Interstate Transactions

Potential economic gains are likely obtainable by interstate water transactions on the Columbia/Snake system, the Colorado, or the Rio Grande Rivers. Recent Supreme Court decisions (Sporhase; El Paso) are rule changes which imply that these potential benefits will be increasingly realized.

The extent of misallocation in each of the above cases can be evaluated if the potential opportunity cost of water differs from marginal value in current uses by more than the cost of the transaction and transportation. Opinion on the degree to which misallocation currently exists is divided. One viewpoint is that restrictions on transfer are presently responsible for significant misallocations. This perspective is reflected in papers in the book edited by Anderson (1983). Howitt et al. (1982) report large potential gains from reallocation of water resources in California.

Others offer more moderate views. Young (1986) emphasized that transaction and transfer costs are larger than many economists estimate and that potential gains from trade may not be all that large.

In summary, four major areas of institutional concern are associated with surface water delivery systems. *First,* a major waste of resources and associated misallocation may be derived from the public subsidies to surface water developments in lieu of transfers. The rising cost of structural solutions, in terms of both capital and environment, is forcing attention toward reallocation. For example, the Los Angeles Metropolitan Water District developed a sudden interest in Imperial Valley water when the Peripheral Canal was rejected. *Second,* instream use rights still are not well defined. *Third,* interstate transactions appear to be only a distant possibility. *Finally,* third party effects from irrigation - induced waterlogging and salinity pose new challenges to traditional water rights systems (Moore, 1972; Young and Horner, 1986).

Ground Water Supply Systems

Ground water provides about 40% of the water withdrawn for irrigation in the United States (Solley et al., 1983). The proportion from ground water in the southern Great Plains (Ogallala-High Plains aquifer) is about 75%. Approximately half of the irrigation water used in the central valleys in Arizona and California is from ground water.

Ground water aquifers are typically exploited by a large number of independent pumpers withdrawing water from the common supply. Aquifers vary greatly in their physical characteristics, so obtaining information on the depth, porosity, hydraulic characteristics, and water quality in these deposits can be costly and time-consuming. The action of one pumper may affect adjacent pumpers, depending on the well spacing, volume of water pumped, and the hydraulic characteristics of the aquifer. The resulting spillovers are a source of potential resource misallocations (Young, 1970; Feinerman and Knapp, 1983).

State/Regional Accounting Stance

In cases where nonrenewable ground water is held in common ownership and utilized by otherwise independent agents, the water resource is "fugitive" and must be captured in order for the user to claim rights to it. A main focus of the ground water management literature has been on built-in incentives for using water now rather than conserving it for the future. The individual user's rights to future use of the pool are indefinite, because other pumpers may capture the water in the meantime. The normal self-interest of individual users is to ignore the opportunity costs of future use and focus on the present.

Unregulated private pumping may deplete ground water resources too quickly because of two additonal factors. The first relates to the potential role of the investment and disinvestment rates for indirect private capital and social infrastructure. Businesses, consumers, and taxpayers may want to match more closely the rate of exhaustion of a stock resource to the rate of depreciation in certain of their fixed assets (schools, hospitals). The second reason relates to the notion of a social rate of time preference which more highly values distant future costs and benefits than does the private individual (Pearce and Nash, 1981). Society may place more value on extending the life of an aquifer than would a private individual pumper.

Institutional arrangements to control the rate of ground water depletion have received relatively little analytic attention. Colorado and several other states with lands overlying the Ogallala aquifer have adopted relatively simple size and spacing regulations for wells.

Beattie (1981) contends there is inadequate justification for regulating ground water withdrawals. His argument for the Ogallala resource was that the rate of lateral migration of water toward a cone of depression is so slow that the presumption of interdependency was irrelevant. Beattie concluded that for this aquifer the fear of future capture of one's water by a neighbor was unfounded, and producers can be assumed to extract the resource at a socially optimal rate. Others remain skeptical of this view. Again, the hydraulic characteristics of the aquifer, pumping rates, and resulting hydraulic gradients are key factors which must be considered in making a valid assessment of this issue.

National Accounting Stance

Young (1985, unpublished) believes that a major misallocation of ground water resources comes from federal policies that have for several decades distorted the costs and returns to ground water extraction. Agricultural support programs raise and stabilize crop prices, thereby reducing risk and incorrectly signaling food scarcity. This effect is compounded by subsidized electricity for pumping, along with low cost credit programs and other assistance to farmers. In this view, a large part of the post-World War II ground water development in both the Great Plains and the southwest was mistakenly encouraged by federal programs tilted toward raising farm incomes and production.

Conjunctive Ground and Surface Water Systems

Reliance on supplemental ground water during seasons or years when surface supplies are less than optimal is common throughout the West. Few analyses focus on institutional issues and potential misallocations related to conjunctive use. For example, extensive ground water development in the river basins in eastern Colorado reached a stage in the mid-1960s in which river flows were being drawn off by pumping from shallow tributary aquifers to the detriment of junior surface right holders. A quasi-market augmentation system adopted a decade ago protects the rights of surface water users while permitting capture of the large economic benefits from ground water use.

Improving Organizational Functioning

The study of organizational behavior related to irrigation systems is in its infancy. Some economists have combined efforts with other disciplines to analyze management of irrigation organizations, with a primary focus on large-scale surface water systems (Maass and Anderson, 1978).

Nonmarket responses to market imperfections may also lead to nonoptimal outcomes. Wolf's (1979) model of nonmarket failure focuses on public agency performance incentives which result in divergence from socially preferable outcomes in terms of allocative efficiency and distributional equity criteria. A general lesson here is that nonmarket solutions may not necessarily be superior to suboptimal market approaches.

Wolf (1979) lists several problems. *First,* products of nonmarket activities are hard to define, and hard to measure independently of the inputs that produced them. *Second,* evidence of quality is elusive because consumer preferences transmitted by market prices are missing; it is difficult to know if public performance is improving or deteriorating. *Finally,* there is no single "bottom-line" for evaluating performance because the public cannot effectively determine the value of public action, and there is seldom a reliable mechanism for terminating unsuccessful programs.

The case of public irrigation projects illustrates the above problems. The Bureau of Reclamation's annual reports, as well as those of irrigation ministries in other countries, document the number of acres irrigated; quantity of water stored or delivered; and the number of farms served, or gross crop revenues. None of these directly answers the essential question, "What is the actual economic return on the public investment?" The most appropriate measure — the realized net social return on public investment — is complex to estimate (requiring large annual sample surveys of farmer profitability) and is not really desired by the agency. Hence, such measures are attempted only by an occasional dissident academician. Even there, however, agreement is lacking on how to measure important elements of the formula, such as interest rates, prices for crops, and opportunity costs of labor and other inputs.

Private Goals of Public Agents

Wolf (1979) refers to the internal goals of an organization as "internalities." These, in addition to the agency's public purposes, provide the motivations, rewards, and penalties for individual performance. Such internal goals are characteristic of any large organization, private or public. Therefore, because of the above performance measures, public inefficiencies are less likely to be corrected than in the private sector.

Specific examples of counter-productive internal goals include budget maximization; overly expensive, high-tech solutions; and nonperformance of duties. In the first example, when profit is not available as a performance measure, the budget often serves as a proxy. Agency heads are often, in fact, provided with staff and prerequisites according to the size of their budgets, reinforcing the incentive distortion. Second, high technology solutions or "technical quality" may become an agency goal. Sprinkler or trickle irrigation systems, for example, may be recommended when less technically efficient methods may be preferable where capital is scarce but labor and water are relatively plentiful. Finally, agency personnel may be persuaded by gifts or other inducements to violate operating rules for a favored few (Wade, 1982).

Spillovers From Public Action

Public agencies, including irrigation projects, also can be a major source of third-party effects. Waterlogging or salination of downslope lands in inappropriately managed public projects is an example (Moore, 1972; Young and Horner, 1986). These problems are even more difficult to resolve when the third party effects are registered in another country as occurred in Mexico due to drainage programs in the U.S. portion of the Colorado River (Oyarzabal and Young, 1978).

Inequitable Distribution of Power

Public sector responsibilities, however noble the intent, may not be exercised scrupulously or competently. Yet the monopoly control of water supplies by public agencies provides certain individuals with so much power over the economic welfare of farmers that procedures to protect those with limited influence must be of prime importance.

Incremental changes to improve the performance of irrigation projects need to focus on system managers and personnel. A start would be to link more closely the rewards received by the system agents with the ultimate profitability of their farmer clients. Another performance parameter might be bonuses contingent on the crop yields in an irrigation project exceeding the average yield for the previous five- to seven-year period by a specified percentage. These bonuses would be sized to take only a fraction of incremental farmer returns, but could provide substantial supplements to water managers' incomes. Providing bonuses tied to the achievement of revenue collecting requirements to the staff of irrigation organizations would be another potential approach.

9. Development and Adoption of Irrigation Technology

Traditionally agricultural innovations have been viewed as products developed and tested in laboratories of universities and industry, appropriately packaged, and then delivered to farmers for adoption. Being an "innovative" farmer has usually meant being the first to adopt someone else's invention. In reality, farmers are inventors of new farming techniques as well as adopters of new technology. This has been especially true with irrigation technology. A Nebraska farmer developed the first center pivot irrigation system because of the frustrations of having to uncouple, carry long sections of irrigation pipe to the next set, and then recouple the sections in order to change the settings. A southern Idaho farmer invented the lateral-move irrigation system for conditions where the center pivot system was not suitable (Feller et al., 1984).

Regardless of whether a new technology has been developed by farmers themselves or by public agencies or private industry, its diffusion through the farm population is usually slow. Even the best agricultural innovations have typically taken ten, fifteen, or twenty years before being widely adopted. For example, hybrid seed corn, perhaps the most important innovation of this century for improving agricultural production, required about fifteen years before it was adopted by virtually every corn grower. Another example is the electronic calculator. Calculators, allowing one to easily make mathematical calculations, have been available since the 1950's. Now, virtually every farmer has at least one, but the major adoption did not take place until the 1970's. Adoption of most innovations usually starts slowly, followed by a significant acceleration, and gradually slows as most users put them into practice (Figure 9.1).

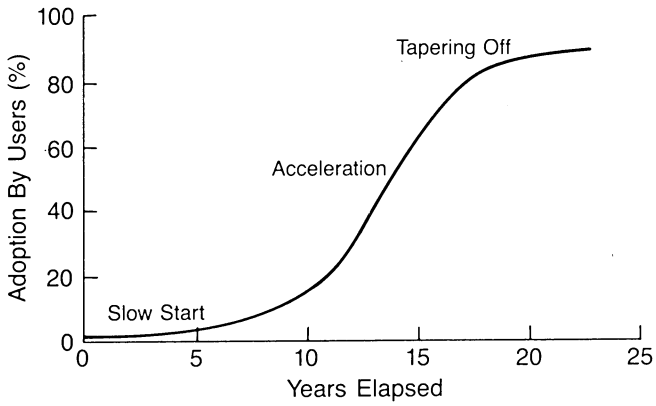


Figure 9.1. The adoption of new technology takes time.

Factors Affecting the Adoption of New Technology

Three elements influence the adoption process: (1) the context within which the innovation occurs; (2) the nature of the innovation; and (3) the characteristics of individuals. The adoption of irrigation technology in light of these factors is summarized in the next few paragraphs.

The Context

The context is a very important influence in the adoption of irrigation technology. The cost of energy to transport and apply water affects the kind of irrigation practices used. Energy costs plus depletion of the Ogallala aquifer have caused some farmers to return to dryland agriculture in the southern Great Plains. The cost of labor influences a farmer's decision to continue to use hand-move irrigation systems, or to change to a center pivot or lateral-move, mechanized system. For example, there may be no incentive for conversion to a more labor saving technology when a farmer has three teenage children at home to move irrigation pipe before and after school. Topography may also affect the adoption of a particular type of irrigation system.

Government farm programs and cost sharing programs are further examples of context variables that influence the way a farmer handles the irrigation system. Many factors are beyond the direct control of the farm operator, yet may be primary factors in his or her decision to adopt or reject new technology.

The Innovation

Irrigation technology has undergone rapid changes over the past few decades. Problems still exist with the use of some of the new technology. Modern, accurate irrigation scheduling, for example, requires accurate estimates of daily plant water use. Monitoring estimates of soil water levels may be difficult or expensive. Capital investments for some types of irrigations systems may be beyond the financial capabilities of many farmers. Some systems work better on certain typographies than on others.

Innovations tend to be adopted more rapidly if they are simple, have a definite advantage over other methods, and good results are immediately visible. New technology also needs to be compatible with previously existing practices. Finally, adoption occurs more quickly if a little bit can be tried at one time, and if the necessary equipment is easily available.

Some irrigation system technology contrasts sharply with these characteristics. Consider modern irrigation scheduling as an example. First, it is quite complex. Either a farmer must understand how to make estimates or measurements of soil water and plant water use, or obtain the services of a consultant. Further, irrigation scheduling has not always had a clear advantage over more conventional ways of deciding on irrigation times and amounts. For example, it's much simpler for the kids to move irrigation pipe before and after school or to have an existing hired person do it on a weekly or 10 day schedule. In fact, most farm operators who have adopted modern irrigation scheduling have had to learn to "appreciate" the desirable qualities of the practice. One such quality is the record of daily ET and soil water estimates, and end-of-the season summaries on a field-by-field basis.

Modern irrigation scheduling requires doing something quite different than just moving sprinklers at morning, noon, or evening. If soils are shallow or plants have very limited root systems, it may mean changing water settings more frequently and perhaps reducing the quantity of water being applied at each irrigation. This may be inconvenient or the farmers may perceive it as a threat to their right to use the long term supply of water. They may be fearful that if irrigation scheduling reduces water application significantly, they may lose their rights to the excess water they no longer need. Irrigation scheduling is divisible, however, in that one can try irrigation scheduling on a small portion of land or for only one season, and for the most part the service is available commercially. The overall characteristics of the innovation, however, suggest that it is likely to be adopted slowly. A Department of Commerce report indicates that, after nearly 20 years, less than 10 percent of farms use commercial scheduling services or media reports (U.S. Department of Commerce, 1986).

The Individual

Past studies of individual adoption behavior reveals that only a few people are innovators — they are anxious to try new ideas and to adapt them once they are seen as useful (Rogers, 1983). At the other end of the scale are late adopters who believe that if it works on everyone else's farm, then it might work on theirs. The earliest adopters of ideas are people who take risks. They have higher educational level or an ability to think through ideas abstractly, envisioning how they might work in their operation. Innovators also tend to have higher incomes, which gives them the flexibility to experiment. This characteristic is also associated with owners of larger farms. In many cases adoption of a new technology gives the innovators a status they would not have otherwise. It is also increasingly clear that innovators travel widely to seek information. They also tend to have higher mechanical skills and are more likely to modify or build the kinds of equipment they need for their operation (Dillman et al., 1987).

Adoption of New Irrigation Technology

Adoption of irrigation technology follows the same historical pattern as adoption of other agricultural technology. A few farmers will try most of the new irrigation technologies that come along; they usually have the resources to absorb some losses due to inappropriate adoption. In some cases innovators will "make" the new technology work by modifying it to fit their particular operation. Others will watch and wait until they are sure the practice is going to work before adopting it. A few will never adopt new technology. In some cases farmers may hold negative attitudes toward adopting "imposed" technology. For example, a new program for improving irrigation efficiencies to reduce deep percolation and salt loading in the Grand Valley of western Colorado allowed government cost-sharing only if "automated" surface irrigation systems were part of the total improvement package. Irrigators purchased automation components with reluctance and did not always install the components in the field. In many cases they found ways to bypass the automation so they could operate their systems manually, much as they had done before the program. Many of these irrigators, had they approached automation with a positive attitude, could have benefited from the new hardware or could have found ways of making useful modifications for their situations.

A contrasting example occurred with the surge flow valves (SFV) for furrow irrigation and low energy precision applicators (LEPA) for center-pivot irrigation systems. The SFVs are equipped with an automatic controller that can be programmed. These two technologies were introduced at the 1979 American Society of Civil Engineers irrigation conference at Albuquerque, NM. Both of these technologies required innovation by the equipment manufacturers and were widely publicized by the state cooperative extension services, the USDA-Soil Conservation Service, irrigation researchers, and by mass communication media. In the High Plains of Texas, a location where the application of both of these technologies is almost ideal, more than 4,000 SFVs (mean market value is about $1,200 each) have been sold, while about 60-70 new LEPA irrigation systems (an approximate cost for a typical ¼ mile system is $40,000 with the LEPA component accounting for about $2,500 of the system cost) have been sold and 30-40 existing center-pivot systems have been converted to LEPA (an approximate cost is $5,500 per unit).[1]

The SFV can improve the distribution of irrigation water on the soils in the area, and because of automation, can decrease the excessive water applications. The SFV system requires underground irrigation supply pipelines and gated pipe, both of which are common to furrow irrigated fields in the Texas High Plains.

The LEPA irrigation system can reduce irrigation applications because of more uniform water distribution and higher application efficiencies. The LEPA system also can reduce the energy used to pump the irrigation water since the application pressure is reduced. The LEPA system requires a center-pivot sprinkler system which is common to nearly 50% of the irrigated land in the Texas High Plains.

These two technological advances have been rapidly adopted in the Texas High Plains because:

1. They require rather modest capital investment costs that can be quickly recovered.
2. They can be easily integrated into the existing irrigation systems and into the irrigation management programs.
3. They each have alternative uses in case the first use does not prove satisfactory to the grower (SFVs can be used as simple automatic irrigation set change valves, and a LEPA system can be converted back to a standard center-pivot system and/or LEPA can be used to apply chemicals in a multifunction mode).
4. They were widely promoted by irrigation district, USDA-Soil Conservation Service, and extension service demonstrations.
5. They were promoted with low-interest loans from the state of Texas (since 1986) to encourage irrigation water conservation.

As indicated earlier, a number of changes are taking place in the development of irrigation technology. Some of this technology is currently being successfully used by irrigators; some new technology is still in the developmental stage and may or may not be adopted by irrigators.

[1] These statistics were obtained from telephone conversations with Mr. Leon New, Texas Agricultural Extension Service, Amarillo, TX, and Mr. Robert Bruno, P&R Valves, Lubbock, TX.

10. Conservation Concepts

Agricultural water conservation has been an especially controversial topic during the past two decades. Some suggest that agricultural water conservation can resolve the water scarcity problem in the arid and semi-arid West. Others argue that even under the best of circumstances, water conservation can have only a limited effect. Part of the controversy about agricultural water conservation can be attributed to misunderstandings and disagreements about what the term means. But even when the meaning of the term is clear, some issues remain unresolved. One involves empirical estimates of how much water can be conserved and another concerns the implementation of agricultural water conservation.

In this section we do not discuss the empirical question of how much water can be saved because it is impossible to know that answer until there is some agreement on how "conservation" is to be defined. This section focuses on the definitional problem and presents suggestions for clarifying the definition. Next, the dilemma surrounding the development of public policies mandating water conservation is discussed.

Defining Agricultural Water Conservation

The concept of agricultural water conservation is not clear because the term "conservation" means different things to various people. Less formal definitions such as "Conservation is wise use" or "Conservation is beneficial use" or "Conservation is avoiding waste" are not helpful since each of these terms substitutes one value laden term such as "wise", "beneficial", or "waste," for the value laden term "conservation." What is "wise" or "beneficial" usually depends upon whom you ask, in just the same way that the definition of "conservation" depends upon whom you ask. For example, someone observing irrigation practices in lowland rice culture and seeing the large quantities of drain water flowing into canals and streams from the fields, might believe that this is evidence of wasteful or unwise use. But to the rice grower who would have to pay more to reclaim that drainage water than he pays for the raw supply, reclamation would be wasteful, while the current practice is eminently wise. This simple example based on costs to farmers illustrates the need to define water conservation precisely if it is to have a common meaning.

It may be possible to obtain common agreement that water conservation involves saving water or using less water. There are at least three definitions of water savings. Two of these are physical while the third is a behavioral concept.

Physical Definitions

Physical or hydrologic definitions tend to result in estimates of potential water savings that could be achieved. Two physical definitions are distinguished by their spatial and locational focus. To understand the distinctions between these definitions, remember that water flows must always balance — that is, the amount of water entering a region or field must always equal the amount of water leaving, assuming that the basic stocks, including soil water, do not change.

Water balance for a growing season or on an annual basis, can be expressed as water supply = disposition.

$$P + AW + SW = ET + LR + (DP - LR) + RO \qquad (10.1)$$

where P = precipitation, AW = applied water or diversions, SW = available soil water, ET = evapotranspiration, LR = leaching requirement, DP = deep percolation, and RO = runoff. ET and LR are essential for maintaining the productivity whereas RO and (DP - LR), or excess deep percolation, are not essential. SW serves as a bank or reservoir that may be drawn down during the growing season and refilled during the noncrop season and thus may be either larger or smaller, or unchanged from one season to the next.

Saving water implies decreasing the amount removed from the water supply (the left side of the equation). Since precipitation cannot be changed and depleted soil water eventually must be replenished, saving water means reducing the diversions or ground water pumped (AW). In order to save water, or reduce AW, it is necessary to reduce one or more of the right hand components. The farm or field is considered in this first physical definition as the fundamental unit.

Conservation Potential

The treatment of consumptive use, or ET, and the leaching requirement is difficult. We will assume that

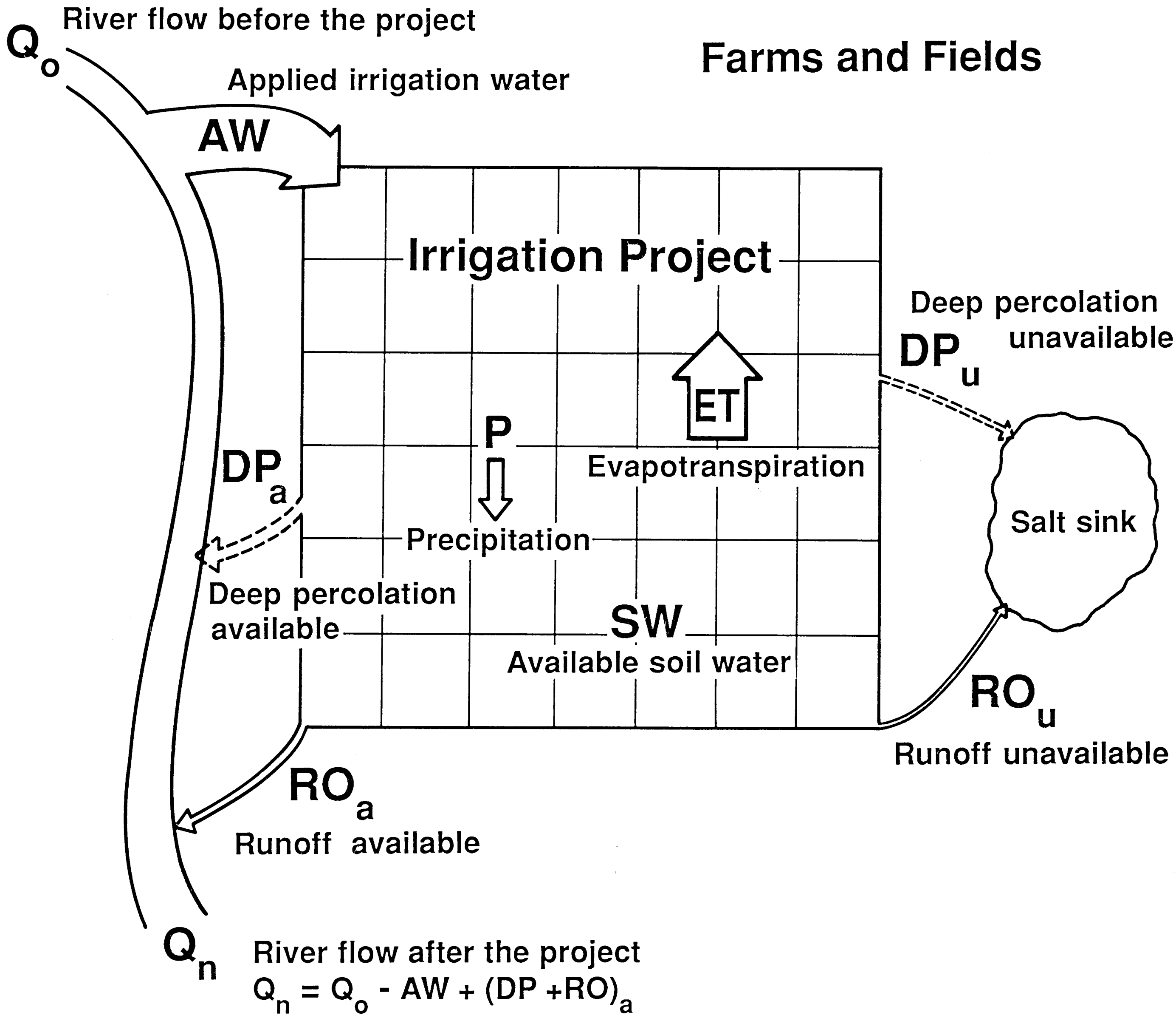


Figure 10.1. The total water supply to the project is the sum of available water from the river (AW) + precipitation (P) + available soil water (SW). This supply is used by evapotranspiration (ET) + deep percolation (DP_a or $_u$) + runoff (RO_a or $_u$). The last two elements may return to the river or ground water and be available for reuse or go to a salt sink and be unavailable for future use. These principles are summarized in Equation 10.3. Drawing by Jane Lenahan, Iowa State University, Ames, Iowa.

conservation should not have negative effects on production. Since reducing ET on specific crops by limiting irrigation or reducing the LR below that essential to maintain an adequate salt balance will reduce crop yields, reducing the first two terms on the right hand side by these practices normally would not be counted as conservation. However, the evaporation component of ET can be reduced by maintaining crop residues on the soil surface, thereby increasing the amount available for transpiration. The net effect of this practice would be a small reduction in ET and would represent water conservation.

On the other hand, saving water in agriculture also can be accomplished by replacing water-intensive crops such as alfalfa with crops such as cotton or beans that require less water, or by growing more salt tolerant crops, thereby reducing the leaching requirement. Such shifts, which reduce ET and leaching terms, would represent water savings. However, replacing water-intensive crops with crops that use less water, or growing more salt tolerant crops may reduce net returns.

One of the difficulties with this physical definition of water conservation is that it is not always clear when reductions in ET or the leaching requirement should be counted as conserved water. A second problem results from the local focus on the field or farm. By defining all reductions in excess deep percolation and runoff as water conservation, we neglect the fact that some or all of the deep percolation or surface runoff may subsequently be reused productively at another downstream location, or that the deep percolation may return to the ground water under the farm from which it was pumped. The fact that water not used consumptively at one location may be available for use at another location greatly complicates the problem of defining water conservation. It means that a local field- or farm-focused definition will usually *overestimate* potential water savings because water reuse possibilities are neglected. Management of groundwater quality also must be considered.

The second physical definition of water conservation accounts for reuse and overcomes the first problem. The area considered in this definition is the hydrologic basin or some geographically logical subsector of that basin. With this definition, excess deep percolation, the LR, and runoff are apportioned according to whether they are available for reuse or not. The water balance equation for this definition is:

$$P + AW + SW = ET + LR + LR_u + (DP - LR)_a + RO_a + (DP - LR)_u + RO_u \qquad (10.2)$$

where the subscript a denotes available for reuse, and the subscript u denotes unavailable for reuse (illustrated in Figure 10.1). This equation can be simplified to:

$$P + AW + SW = ET + DP_a + RO_a + DP_u + RO_u \qquad (10.3)$$

In the above equation, the conservation potential includes only that portion of the deep percolation and runoff that is not available for reuse because it is lost to saline sinks, to deep sediments from which pumping is not possible, or to other sites from which it cannot be retrieved. Obviously, when reuse is considered, the potential for water conservation is reduced, since only a fraction of the deep percolation and runoff is included in the measure of conservation potential.

While this definition overcomes the reuse problem in a legitimate way, some ambiguities remain. The issue of how changes in consumptive use should be treated remains, although reductions in evaporative losses from canals and phreatophytes (water-loving plants that grow in flood plains and extract water from the water table) would be included as savings. An additional problem lies in the fact that it is not always economical to reuse runoff or deep percolation. Typically, when water percolates through soil its quality is degraded, and energy is required to recover this water from the ground water or receiving stream. Surface runoff also may have one or both of these same characteristics.

By focusing on potential quantities of water that could be saved, both physical definitions neglect the fact that it is usually costly to save water. As a result, estimates of potential savings may not be very useful if the costs of saving water are higher than the cost of obtaining supplemental water in other ways. Also, water is a renewable resource except where ground water mining is occuring. This problem leads to a third possible definition of water conservation — a behavioral definition.

A Behavioral Definition

The behavioral definition of water conservation focuses on using water more economically, rather than on conserving water. Economizing means using or managing water in a way that results in maximum net returns or profits. Thus, water is said to be used or managed in an economically optimal fashion. Optimal levels of water use are determined by a variety of factors, including physical factors such as soil type and uniformity, climatic conditions, and crop type. In addition, optimal levels of use are critically influenced by the price of water and the profits which can be obtained by using it in irrigated agriculture. The notion of optimal use (or economically efficient use) recognizes the fact that when the price of water rises and other factors remain the same, irrigators have an incentive to economize on water use resulting in water savings.

Economizing can take two general forms. First, growers may substitute other inputs for water. Changes in irrigation technology sometimes involve the substitution of capital and labor for water. When growers decide to manage irrigation water more intensively, they are substituting some increment of their own farming and managerial skills for water. But such substitution is induced only when the cost of water is high enough to provide an incentive for more intensive management in terms of a substantial monetary pay-off.

In addition to substitution, economizing can also occur as a result of absolute reductions in water use.

A grower may elect to limit irrigations even though some crop water stress and subsequent reduction in crop yield may occur. Or the grower may quit growing water intensive crops and grow crops that require less water. The grower may take land out of irrigated agriculture altogether.

An important feature of this behavioral definition of water conservation is that it resolves the question of when reductions in consumptive use can be considered as conservation. Reductions in consumptive use are properly considered conservation whenever they occur as a result of economizing. The economizing definition may be preferable to the physical definitions because it reflects what will actually happen in a free economy where profit represents the driving force. The economizing definition is exactly analogous to the commonly accepted meaning of the term "energy conservation."

The price of most agricultural water supplies may increase in the immediate future in response to past and future increases in the price of energy, as well as to the increased competition for water. As growers responding to this price increase by economizing, conservation will result independent of what policies are pursued. Some conservation, then, is inevitable. But there remains one difficulty. Decisions about agricultural water use are made at the farm level. This means, as previously noted, that reuse possibilities will be ignored, except for on-farm reuse systems, in economizing decisions. No grower will willingly buy an acre foot of water which doesn't contribute its worth to the operation just to preserve a neighbor's water supply. This situation creates an important policy dilemma.

A Policy Dilemma

Any increase in the price of water will likely mean that some conservation will occur even in the absence of policies mandating it. However, this conservation may alter fundamentally the patterns of water use since the interrelatedness of water uses and reuses will be ignored. On the other hand, if water conservation is publicly mandated, this interrelatedness of use can be accounted for by adopting policies which direct water conservation efforts towards saving water that is not available for reuse. To be effective, such policies will probably have to involve some type of centralized regulation of water use at the farm level. The expense of the bureaucracy needed to create and enforce such regulations will be very high — perhaps even higher than the costs of developing new supplies. In other words, efforts to account for reuse in water conservation policies may end up costing more than the water they save would be worth. The alternative approach, which will usually be less costly, is to recognize that some water conservation will occur as a consequence of increasing water prices and simply ignore the reuse issue. Such an approach may create water right problems and impose hardships on users who rely on return flows, but the costs of avoiding those hardships may be quite high.

Conclusions

Three main points emerge from this discussion of agricultural water conservation. *First,* policy debates and arguments about agricultural water conservation are often hopelessly confused and compromised by the fact that there is no agreement on what actually constitutes water conservation and the beneficiaries of such conservation. Any productive discussion of the topic must begin with an accepted definition of water conservation and how the conserved water is to be used. *Second,* water savings or conservation will almost inevitably occur as a result of an increase in the price of water and the economizing behavior such price increases induce. Since these savings will be made at the farm level, basin or regional reuse possibilties will be ignored. *Third,* public policies on water conservation which attempt to account for regional reuse may be extremely costly to implement effectively. The results they achieve may, in many instances, not be worth the costs of achieving them.

11. Evaluating Alternative Strategies, Institutions, and Practices

Evaluating alternative strategies, institutions, and practices for effective use of water first requires identifying the goals and objectives to be achieved. These goals and objectives may be for an irrigation project, a community, a hydrologic basin, an entire river basin, a geographic or political area, or for a nation. Effective use of water implies productive or beneficial use of water with minimal degradation of water quality and without waste of water. In irrigated agriculture, effective use of water involves minimizing the amount of water diverted to unrecoverable places, or the quantity of water that is made available for reuse as described in Section 10. Since the number of alternative approaches to be considered depends on the scope and viewpoint, a simple example will be used to illustrate the complexity and some resulting effects and requirements of alternative approaches for changing practices and policies to achieve desired benefits.

Example Case

In this example, we have assumed that there is a need to obtain 10,000 acre-feet of water for a new beneficial use such as a domestic or municipal water supply, a new industry, a new crop to be grown on new land, or expansion of existing crop area. We assumed that this water will be required either above or downstream from a 50,000-acre irrigation project along a river, and that this project is the only potential source of water for the new use. At issue is what changes in the irrigated agricultural area will be required to generate the 10,000 acre-feet of water and how can these changes be implemented at optimal cost and minimum burden to the groups involved. Detailed calculations are presented in tables in Appendix 3. The results are summarized below. The data for these tables were computer generated and the number of digits does not signify any degree of accuracy.

Crop, Water Use, and Irrigation System Data

Crops

For simplicity, we assumed that only four crops are grown in the existing project: (1) alfalfa; (2) citrus; (3) sugar beets; and (4) wheat. The distribution of these crops is summarized in Table 11.1.

Evapotranspiration, Leaching Requirements, and Water Requirements

The estimated average seasonal ET, leaching requirement, and irrigation water requirement for the above crops based on surface irrigation systems also are summarized in Table 11.1. Rainfall was assumed to be zero for this arid area.

Volumes of Water Diverted and Consumed

For simplicity, we assumed that the project had a lined main canal and a pipeline conveyance system so that the conveyance losses would be minimal and could be neglected. We assumed that the deep percolation above the leaching requirement and runoff (DP and RO) averaged 40% of the applied water for alfalfa, citrus, and wheat and 45% for furrowed-irrigated crops

Table 11.1. Example irrigation project data and base data

Crop	Percent of area (%)	Crop area (acres)	ET[a] (feet)	E_i[b] (%)	Total (feet)	LR[c] (feet)	Water requirement per acre (ac-ft)	Water requirement Total (ac-ft)
Alfalfa	40	20,000	5.0	60	8.3	0.5	8.8	176,667
Citrus	20	10,000	4.0	60	6.7	0.6	7.3	72,667
Sugar beets	20	10,000	3.0	55	5.5	0.2	5.7	56,545
Wheat	20	10,000	2.0	60	3.3	0.3	3.6	36,333
Total		50,000						342,212

[a]Evapotranspiration.
[b]Irrigation efficiency.
[c]Leaching requirement.

like sugar beets and beans. We assumed that 20% of both deep percolation including the LR and runoff became unavailable for reuse.

For convenience, the ratio of evapotranspiration (ET) to applied water (AW) is called "irrigation efficiency" (E_i), or $E_i = 100$ ET/AW. Thus, E_i is 60% for alfalfa, citrus, and wheat and 55% for beans and sugar beets. Treatment of the LR is more complex because the deep percolation resulting from nonuniform water application will provide most of the LR. In this example, to maintain the simplicity, we have assumed that adequate leaching would occur at the lower end of the field by the application of ET + LR. The reduction in the total water supply is called "net depletion." A summary of the volumes of water diverted, consumed, return flow, and net depletion for the base conditions is presented in Appendix Table A3.1.

Alternatives to Obtaining a Water Supply for Special Use

Four simple alternatives are explored for making 10,000 acre-feet of water, or 4.5% of the net depletion, available for the special use. These alternatives are:

A. Require irrigation efficiencies of all crops to be increased 10 percentage points (from 60 to 70, or 55 to 65%).

B. Substitute 2,600 acres of field beans (ET = 1.5 ft.) for alfalfa, reducing the area of alfalfa to 17,400 acres.

C. Substitute 1,300 acres of field beans for alfalfa reducing the area of alfalfa to 18,700 acres, and increase irrigation efficiencies of all crops by five percentage points (60 to 65 and 55 to 60%).

D. Reduce the irrigated area by 2,300 acres, eliminating whole farms with no change in base conditions for remaining farms.

There are other options that can be considered such as limiting irrigations to reduce yields slightly and reducing the leaching requirement until some effects of salinity on crop yields begin to occur. However, these options require more complex analyses involving crop response to water deficits at different growth stages and responses to increasing salinity. The purpose of this example is to illustrate that even with simple alternatives, solutions to water conservation problems are not readily apparent.

Detailed data for base conditions and for the above alternatives are presented in Appendix Tables A3.1 to A3.5. The effects of changes on flow volumes, depletion of water, and reductions in depletions caused by the above actions are summarized in Table 11.2.

Evaluation of Alternatives

Detailed economic and environmental analyses of the impacts of implementing the above alternative actions cannot be presented in this report. Only the effects on water volumes are presented, along with some comments on the issues that must be considered in implementing the alternatives.

For Alternative A, if all irrigation efficiencies are to be increased on 50,000 acres, the funds available for annual investments per acre, for capital and water management improvements and administration of this alternative will be very sensitive to the value of the water saved and the cost of implementing this practice over a large area.

If 2,600 acres of field beans are substituted for alfalfa, and flow diversion is reduced accordingly (Alternative B), the desired water would be released. This change may be a more viable option to consider depending on administrative costs because only about 5% of the cropland would be affected.

Table 11.2. Effect of alternative actions on net depletion of water by an irrigation project

Alternative	Total diversion (ac-ft)	Total ET[a] (ac-ft)	Return flow (ac-ft)	Depletion of water: Net (ac-ft)	Depletion of water: Decrease (ac-ft)
Base conditions	342,212	190,000	121,770	220,442	--
Alternatives:					
A. Increase E_i[b] 10 points	295,725	190,000	84,580	211,145	9,297
B. Change crops	326,265	180,900	116,292	209,973	10,469
C. Increase E_i 5 points and change crops	309,764	185,450	99,451	210,313	10,129
D. Reduce irrigated land area	326,470	181,260	116,168	210,302	10,140

[a]Total evapotranspiration.
[b]Irrigation efficiency.

The option both to change crops and to increase irrigation efficiencies (Alternative C) would have the same disadvantages as option Alternative A, but some advantages of Alternative B. The cost of implementing this dual change may be higher than implementing Alternative A. Thus, it may not be an economically viable option.

The option to remove 2,300 acres from production (Alternative D) by having the new water users purchase the water rights may be the simplest and least costly alternative to implement. However, there are externalities that must be considered. For example, the cost of maintaining the existing project diversion and conveyance system would have to be borne by the remaining growers, which would increase their annual operation and maintenance costs about 6%.

The above examples illustrate the complexity of assessing alternatives to make additional water available for a new use. They also illustrate the potential difficulties and costs of attempting to legislate changes from a regional or national viewpoint.

Increasing Effective Use of Water in Semiarid Irrigated Areas

In semiarid irrigated areas, there are two ways to increase the effective use of water. There are: (1) retention of all precipitation on the land; and (2) reduction of evaporation losses by maintaining crop residues on the soil surface. These practices, which were developed for nonirrigated agriculture, when combined with the best irrigation practices, can reduce the amount of irrigation water that needs to be pumped or withdrawn from streams. The practice of furrow-diking to eliminate or minimize runoff, for example, has been implemented on several hundred thousand acres of irrigated land in the Texas panhandle where intense rainfall often results in significant runoff.

Similarly, the combination of alternating dryland and irrigated use of some fields can increase the effective use of precipitation. For example, an irrigated crop is grown to produce sufficient crop residues, which, when maintained on the surface, will reduce evaporation during the following fallow, or noncropped, period. The result of this practice can increase the amount of precipitation stored during the fallow period from 20 to 50%, which may be sufficient to produce a reasonable crop without irrigation. This practice is beginning to be implemented in some areas of the Great Plains where water for irrigation is limited or expensive.

Other Considerations

In addition to water consumption, most uses of water also affect the quality of water. For example, since ET removes essentially pure water, the concentration of salts in the remaining return flow is increased. The increase in salinity is proportional to the ratio of applied water (AW) to the evapotranspiration of irrigation water (ET_i), or AW/ET_i times the original salinity level. When the return flow mixes with the original stream flow, the salinity of the stream flow is increased by an amount that depends on both the return flow and the stream flow rates. Estimates of the potential damage, or loss of value, of the water have been made for some areas such as the lower Colorado River basin. Typically, the potential damage is greatest when water is to be used for municipalities, because the water must be treated or the life of water-related appliances is reduced.

The potential cost to agriculture is related to the reduction in crop yields caused by an incremental increase in salinity. These costs depend on the type of crops being grown and their market values. The analyses of these costs also must be considered in evaluating alternative practices to make more effective use of water in irrigated agriculture.

Conclusions

Evaluation of alternative strategies, institutions, and practices first requires identifying the problem, or apparent problem, followed by detailed analyses of the effects and costs of implementing physical and institutional changes required to solve the problem. Solution approaches require: (1) agreement on terminology; (2) agreement on goals, objectives, and priorities; (3) identification of possible alternative actions; and (4) evaluation of the potential costs and benefits to be derived from implementing one or more actions.

The evaluation of alternative strategies to increase effective use in irrigated agriculture involves many variables. The general practice of providing opportunities for private individuals and political bodies to independently evaluate the potential costs and benefits of establishing institutions and implementing practices to achieve the target benefits should be encouraged. The potential costs of mandating and monitoring changes in irrigation practices may greatly exceed the benefits. All potential improvements in both dryland and irrigated agriculture technology that increase water use efficiency, of production per unit volume of water consumed, should be encouraged through ongoing development and technology transfer programs.

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Appendix 2: Irrigation Efficiency

Many different irrigation efficiency terms have been defined in the irrigation literature. The same term may have been used differently by different specialists. Today, irrigation engineers and scientists must use care to be sure that statements about irrigation efficiency are understood as the originator intended. Because of this potential for confusion, the Task Force that prepared this report decided at the outset of their work that they would try to avoid use of "irrigation efficiency" terms in the text of the document.

Most efficiency terms are indices that are used to compare the effectiveness of similar irrigation systems. The absolute values of the efficiency usually have less meaning than their relative values. As examples from other walks of life, the internal combustion engine converts the chemical energy of gasoline to the mechanical energy of the driveshaft of an automobile with efficiencies that range from about 12 to 25%. The average oil- or gas-heated home may be converting the chemical energy of the petroleum to heat with an efficiency of about 50% (Wark, 1977). Yet most of us do not hesitate to use our cars or our furnaces. While we would be happy to get a few more miles per gallon, or see smaller heating bills, we do not expect efficiencies near 100%.

Since some readers of this report will have read or listened to discussions of the adverse effects of low irrigation efficiencies, they may want to know more about the definitions of the term and what low efficiency values represent. The following discussion of irrigation efficiency, as the term (or terms) is generally understood by irrigation engineers in the United States, is presented for this purpose.

Generally, to be effective, a single irrigation of a cropped field should result in a large fraction of the applied water remaining available in the soil for use by the crop being grown. The crop extracts this water and some of the water evaporates from the soil surface in a process called evapotranspiration (ET). When the soil water has been depleted to a level that begins to affect crop growth, another irrigation is needed. The water actually used in ET, relative to the total applied, is generally called "irrigation efficiency." The water that is potentially available for ET (or the water stored in the soil root zone by an irrigation), relative to the total water applied to the field in the irrigation process, has been called the application efficiency or water application efficiency (Israelsen, 1950).

As indicated in this report, water that is not stored in the root zone by an irrigation may serve other beneficial purposes such as leaching. Thus, such water is not necessarily wasted and low application efficiencies do not always mean that water is being wasted. High values of application efficiency usually indicate that the surface runoff and deep percolation from an irrigation are small. Small values of runoff and percolation are usually desirable, although deep percolation may be required to leach excess salts from the root zone.

As defined, an irrigator could easily obtain very high values of application efficiency by inadequate irrigations. As an extreme example, a bucket full of water applied to dry soil on a field will all become available for ET. But, if the field is regularly underirrigated, very frequent irrigations will be required to prevent crop water stress. Frequent irrigations require unacceptably high labor inputs for most irrigation systems. Light irrigations also may result in less extensive crop root development, which limits the plants' access to nutrients and limits crop tolerance to drought. Thus, other terms have been formulated to indicate the volume of water stored in the root zone by an irrigation, relative to the volume that the root zone was capable of holding at the time of irrigation. The water storage efficiency and the water requirement efficiency are terms that represent this concept.

On most fields, ideal irrigations would add the same volume of water to each unit of soil. In other words, irrigations should be uniform. Terms that are used to indicate uniformity include several different uniformity coefficients, distribution uniformity, or distribution efficiency.

Irrigation is sometimes used for economically beneficial purposes other than supplying crop ET or leaching salts. Use of sprinkler applications to cool heat sensitive crops or prevent freeze damage are common examples. Many of the professional arguments about efficiency definitions and their interpretations have come about because of questions as to whether the efficiency values should be adjusted upward for such non-ET uses of water, or whether lower efficiency should be accepted when irrigation has such auxiliary purposes.

From the foregoing, it should be apparent that the effectiveness of an irrigation can seldom be described by a single irrigation efficiency term. Irrigation designers and managers should try for compromises that will produce acceptably high values of application and storage efficiencies and uniform water distribution at an affordable cost. If there must be decisions that trade off between the relative amounts of runoff and percolation, as is often the case, conditions at a given site will frequently determine which should be sacrificed.

In addition to on-farm efficiencies, the effectiveness of water delivery to the farm, or use of return flows from irrigated farms is important and often needs to be quantified. Jensen (1984) defined "effective irrigation efficiency" for a project on a river basin to enable accounting for return flows from irrigated fields that are reused by downstream diverters.

Seepage and evaporation of water from conveyance channels to the farm and on the farm are generally undesirable. Conveyance efficiency describes the fraction of the water pumped or diverted that reaches the fields to be irrigated.

It should also be evident from material presented in this document that low values of irrigation efficiency do not necessarily result in losses of water to further economic use by the public, and that changing irrigation practice to increase efficiency will not necessarily result in substantial savings of water. Low values of irrigation efficiency, as the term is usually used by the layperson, implies that water is seeping from conveyance channels, running off the surface of irrigated fields, or seeping through soils to depths at which crops cannot reach it. Most such water returns to water bodies that can be reused for economic purposes. Often, in fact, such "losses" actually extend the length of time that water is available in streams that are low or dry during parts of the year, thus making the flow rate more uniform.

Appendix 3: Computations for Example Case

Table A3.1. Computations for the example case presented in Section 11 (base line conditions)

Crop	Crop area (acres)	ET[a] (feet)	E_i[b] (%)	Total (feet)	LR[c] (feet)	Water requirement Depth (feet)	Water requirement Volume (ac-ft)
Alfalfa	20,000	5.0	60	8.3	0.5	8.8	176,667
Citrus	10,000	4.0	60	6.7	0.6	7.3	72,667
Sugar beets	10,000	3.0	55	5.5	0.2	5.7	56,545
Wheat	10,000	2.0	60	3.3	0.3	3.6	36,333
Total	50,000						342,212
DIVERSION AND RETURN FLOW VOLUMES:							
Project diversion							342,212
Total evapotranspiration							190,000
Excess water, deep percolation, and runoff (DP and RO)							152,212
Unavailable deep percolation and runoff, 20 %							30,442
Return flow							121,770
Net depletion of water by the project							220,442

[a]Evapotranspiration.
[b]Irrigation efficiency.
[c]Leaching requirement.

Table A3.2. Computations for the example case presented in Section 11. Alternative A. Improve irrigation efficiency 10 percentage points.

Crop	Crop area (acres)	ET[a] (feet)	E_i[b] (%)	Total (feet)	LR[c] (feet)	Water requirement Depth (feet)	Water requirement Volume (ac-ft)
Alfalfa	20,000	5.0	70	7.1	0.5	7.6	152,857
Citrus	10,000	4.0	70	5.7	0.6	6.3	63,143
Sugar beets	10,000	3.0	65	4.6	0.2	4.8	48,154
Wheat	10,000	2.0	70	2.9	0.3	3.2	31,571
Total	50,000						295,725
DIVERSION AND RETURN FLOW VOLUMES:							
Project diversion							295,725
Total evapotranspiration							190,000
Excess water, deep percolation, and runoff (DP and RO)							105,725
Unavailable deep percolation and runoff, 20 %							21,145
Return flow							84,580
Net depletion of water by the project							211,145
EFFECT OF CHANGES IN IRRIGATION EFFICIENCY:							
Decrease in net depletion of water by project							9,297

[a]Evapotranspiration.
[b]Irrigation efficiency.
[c]Leaching requirement.

Table A3.3. Computations for the example case presented in Section 11. Alternative B. Substitute some field beans (ET = 1.5 ft) for alfalfa

Crop	Crop area (acres)	ET[a] (feet)	E_i[b] (%)	Total (feet)	LR[c] (feet)	Water requirement Depth (feet)	Water requirement Volume (ac-ft)
Alfalfa	17,400	5.0	60	8.3	0.5	8.8	153,700
Beans	2,600	1.5	60	2.5	0.2	2.7	7,020
Citrus	10,000	4.0	60	6.7	0.6	7.3	72,667
Sugar beets	10,000	3.0	55	5.5	0.2	5.7	56,545
Wheat	10,000	2.0	60	3.3	0.3	3.6	36,333
Total	50,000						326,265

DIVERSION AND RETURN FLOW VOLUMES:	
Project diversion	326,265
Total evapotranspiration	180,900
Excess water, deep percolation, and runoff (DP and RO)	145,365
Unavailable deep percolation and runoff, 20 %	29,073
Return flow	116,292
Net depletion of water by the project	209,973
EFFECT OF CHANGES IN TYPE OF CROPS GROWN:	
Decrease in net depletion of water by project	10,469

[a]Evapotranspiration.
[b]Irrigation efficiency.
[c]Leaching requirement.

Table A3.4. Computations for the example case presented in Section 11. Alternative C. Substitute some field beans (ET = 1.5 ft) for alfalfa and increase irrigation efficiencies five percentage points

Crop	Crop area (acres)	ET[a] (feet)	E_i[b] (%)	Total (feet)	LR[c] (feet)	Water requirement Depth (feet)	Water requirement Volume (ac-ft)
Alfalfa	18,700	5.0	65	7.7	0.5	8.2	153,196
Beans	1,300	1.5	65	2.3	0.2	2.5	3,260
Citrus	10,000	4.0	65	6.2	0.6	6.8	67,538
Sugar beets	10,000	3.0	60	5.0	0.2	5.2	52,000
Wheat	10,000	2.0	65	3.1	0.3	3.4	33,769
Total	50,000						309,764

DIVERSION AND RETURN FLOW VOLUMES:	
Project diversion	309,764
Total evapotranspiration	185,450
Excess water, deep percolation, and runoff (DP and RO)	124,314
Unavailable deep percolation and runoff, 20 %	24,863
Return flow	99,451
Net depletion of water by the project	210,313
EFFECT OF CHANGES IN TYPE OF CROPS GROWN:	
Decrease in net depletion of water by project	10,129

[a]Evapotranspiration.
[b]Irrigation efficiency.
[c]Leaching requirement.

Table A3.5. Computations for the example case presented in Section 11. Alternative D. Reduce the irrigated area by 2,300 acres

Crop	Crop area (acres)	ET[a] (feet)	E_i[b] (%)	Total (feet)	LR[c] (feet)	Water requirement Depth (feet)	Water requirement Volume (ac-ft)
Alfalfa	19,080	5.0	60	8.3	0.5	8.8	168,540
Citrus	9,540	4.0	60	6.7	0.6	7.3	69,324
Sugar beets	9,540	3.0	55	5.5	0.2	5.7	53,944
Wheat	9,540	2.0	60	3.3	0.3	3.6	34,662
Total	47,700						326,470
DIVERSION AND RETURN FLOW VOLUMES:							
Project diversion							326,470
Total evapotranspiration							181,260
Excess water, deep percolation, and runoff (DP and RO)							145,210
Unavailable deep percolation and runoff, 20 %							29,042
Return flow							116,168
Net depletion of water by the project							210,302
EFFECT OF CHANGES IN IRRIGATION EFFICIENCY:							
Decrease in net depletion of water by project							10,140

[a]Evapotranspiration.
[b]Irrigation efficiency.
[c]Leaching requirement.