Chapter 1
Introduction to Irrigation

1.1 Introduction

Irrigation is the supply of water to crops by artificial means. It is designed to permit the desired plant growth in arid regions and to offset drought in semiarid regions or subhumid regions. Even in areas where average seasonal precipitation may seem ample, rains are frequently unevenly distributed, or soils have low water holding capacities so that traditional rainfed agriculture is a high-risk enterprise. Irrigation provides a means for stable food production. In some areas, irrigation prolongs the effective growing season. With the security provided by irrigation, additional inputs like higher producing varieties, additional fertilizer, better pest control, and improved tillage, become economically feasible. Irrigation reduces the risk of these expensive inputs being wasted by drought.

On a global scale, irrigation has a profound impact on fresh water supplies, world food production, and the aesthetics and value of landscapes. One-third of the world's food comes from the 21% of the world's cultivated area that is irrigated (Table 1.1). In the U.S., irrigated agriculture accounted for about half of the total value of crop sales on 28% of harvested crop land in 2012 (USDA, 2019).

Table 1.1. Worldwide distribution of irrigated areas in 2017 (adapted from FAO, 2021).

	Irrigated Area (millions of acres)	Percent of Cropped Lands	Percent of World Total
Asia	574	39	71
America	128	14	16
Europe	56	8	7
Africa	39	6	5
Oceania	8	10	1
World	806	21	100

Irrigation has turned many of the earth's driest and most fertile lands into important crop producing regions. For example, Egypt could grow virtually no food without water drawn from the Nile or from underground aquifers. California's Central Valley and the Aral Sea basin—the fruit and vegetable baskets of the United States and the former Soviet Union—would produce little without irrigation. The world's major grain producing areas of northern China, northwest India, and the U.S. Great Plains would drop by one-third to one-half without irrigation to supplement rainfall. Irrigation fills a key role in feeding an expanding world population and seems destined to play an even greater role in the future.

As practiced in many places, however, irrigation is still based largely on traditional methods which fail to measure and optimize the supply of water to satisfy plant water demands. Unmeasured irrigation tends to waste water, nutrients, and energy, and may cause soil degradation by waterlogging, erosion, and salination. The vital task of assuring adequate global food production must include a concerted effort to modernize irrigation systems and improve water management. These improved techniques will help achieve sustainable and efficient production while protecting the environment. New systems must be based on sound principles and designs to optimize irrigation in relation to essential inputs and operations while guaranteeing sustainability of irrigated agriculture. Water and soil must be recognized as vital, precious, and vulnerable resources and managed accordingly.

In recent years, revolutionary developments have taken place in the design and management of irrigation. Understanding of the interactive relationships among soil, plant, and climate regarding the ideal disposition and utilization of water continues to evolve. These scientific developments have been paralleled by a series of technical innovations in water control which make it possible to establish and maintain nearly optimal soil moisture conditions.

1.2 Role of Irrigation

The irrigation process consists of introducing water to the soil profile where plants can extract it to meet their needs, mainly evapotranspiration. An important goal of irrigators is to design and manage their irrigation system to optimize placement and timing of applications to promote growth and yield while protecting against soil erosion, salination, water quality degradation, or other detrimental environmental impacts. Since physical circumstances and socioeconomic conditions are site specific, there is no single answer to designing, developing, and managing an irrigation system. In all circumstances, however, the factors and principles involved are universal.

The practice of irrigation has evolved gradually toward improved control over plant, soil, and even weather variables. The degree of control possible today is still only partial because of unpredictable extremes in the weather. Modern irrigation is a sophisticated operation, involving the monitoring and manipulation of numerous factors impacting crop production. With the continuing loss of suitable land and water and the rising demand for agricultural products, the search for new knowledge on how to improve irrigation and the need to apply this new knowledge have become increasingly urgent.

Any attempt to irrigate must be based on a thorough understanding of soil-water-plant relationships. The movement of water, once applied, consists of a sequence of dynamic processes beginning with the entry of water into the soil, called infiltration. The rate of infiltration is governed by the rate at which water is applied to the soil surface, as long as the application rate does not exceed the capacity of the soil to absorb it. An important criterion for a sprinkler or microirrigation system is to deliver water at a rate that will prevent ponding, runoff, and erosion.

After infiltration, water normally continues to move because of gravity and hydraulic gradients in the soil. Water moves downward and, with some irrigation systems, laterally in a process called redistribution. In this process the relatively dry deeper zone of the soil profile absorbs water draining from wetter zones above. Within a few days (depending on the irrigation system and management) the rate of flow becomes so low as to be negligible. The water content of the wetted zone as flow becomes negligible is termed the field capacity and represents the upper limit of the soil's capacity to store water. Field capacity is normally higher in clay than in sandy soils.

Any water draining below the root zone is generally considered to be a loss from the standpoint of immediate plant water use. It is not necessarily a final loss, however. If the area is underlain by an exploitable aquifer, the water percolating below the root zone may eventually recharge the aquifer and be recovered by pumping. Some deep percolation may later return to streams or drainage systems. This quantity of water plus surface runoff from irrigated agriculture is called return flow. Where the water table is close to the soil surface, some water may enter the root zone by capillary rise up from the saturated zone below the water table and supply a portion of the crop's water requirement. This process of subirrigation, however, may infuse the root zone with salts. Water flowing down through the root zone may leach soluble salts or crop nutrients and degrade the quality of groundwater.

Properly designed and managed, modern irrigation methods can increase crop yields while avoiding waste, reducing drainage, and promoting integration of irrigation with essential concurrent crop management operations. The use of degraded water has become more feasible, and coarse-textured soils, steeply sloping lands, and stony soils, previously considered not irrigable, are now productive. Such advances and their consequences were unforeseen only a few decades ago.

1.3 Irrigation Development

For thousands of years, irrigation has contributed substantially to world food production. Historians note that irrigation was one of the first modifications of the natural environment undertaken by early civilizations. Several millennia ago, irrigation permitted nomadic tribes to settle in more stable communities with assurance of annual crop productivity. Initial attempts at irrigation were rudimentary, consisting of ponding water in basins enclosed by low earthen dikes.

The earliest societies to rely successfully on irrigation were located in four major river basins: the Nile in Egypt around 6,000 B.C.E., the Tigris and Euphrates in Mesopotamia about 4,000 B.C.E., the Yellow River in China around 3,000 B.C.E, and the Indus in India approximately 2,500 B.C.E. In Mexico and South America, irrigation was practiced by the Maya and Inca civilizations more than 2,000 years ago. In Iran, ganats, 3,000 year-old tunnels to bring water from the mountains to the valley, are used to this day (Kuros, 1984). Earthen dams to store surface water were first constructed in the second and third centuries in Japan to irrigate rice. In Central Europe, irrigation was documented as early as the third century C.E. (Csekö and Hayde, 2004).

In North America, irrigation is known to have existed among Native Americans of the southwest as early as 1200 B.C.E. Early Spanish explorers found evidence of irrigation canals and diversion points along rivers. The Spaniards introduced new irrigation methods and irrigated crops such as grapes, fruits, vegetables, olives, wheat, and barley. As in other areas of the world, irrigation made it possible for Native Americans to develop settlements and enjoy a more secure food source.

At the beginning of the 1800s, the total irrigated area in the world was estimated at about 20 million acres (Gulhati, 1973). Up to that time most irrigation works were small systems. Irrigation began to expand in many countries in the nineteenth century and took on new dimensions in terms of the amounts and methods of water diversion and management. The first barrages, short diversion dams, were built in the Nile Delta in about 1850. About the same time in India, several irrigation canal systems were constructed. The Lower Chanab Canal in Pakistan was the first canal system intended strictly for arid land not previously cultivated. In 1847 Mormon colonies began irrigating in Utah. Their efforts expanded into California, Nevada, Idaho, Wyoming, Arizona, New Mexico, and Canada. German immigrants started an irrigation colony in Anaheim, California, in 1857, and an irrigation colony was started in 1870 at Greeley, Colorado. At the end of the nineteenth century, irrigation in the world was estimated at 100 million acres, a fivefold increase during the century (Gulhati, 1973).

Historians sizing up the twentieth century will almost certainly include irrigation as one of the century's characteristics. During the first half of the century, irrigated area worldwide rose to more than 230 million acres. The surge continued in the second half of the century with over 800 million acres in 2017 (Table 1.2).

Many countries—such as China, Egypt, India, Indonesia, Israel, Japan, Korea, Pakistan, and Peru—rely on irrigation for more than half of their domestic food production. Countries with 10 million irrigated acres or more are tabulated in Table 1.3. Large areas of irrigated lands in southeast Asia lie in the humid equatorial belt. These areas have monsoon climates with very large totals of annual rainfall,

Table 1.2. Growth in irrigated land and world population since 1900 (adapted from FAOSTAT, 1999; FAO, 1998, 2021).

Year	Irrigated Area (millions of acres)	Population (billions)
1900	100	1.5
1950	235	2.5
1970	422	3.7
1990	598	5.3
1997	669	5.9
2017	806	7.5

but portions of the year are dry. In these countries, paddy or flooded rice is the dominate irrigated crop. Countries like China, Korea, Japan, Indonesia, and the Philippines have long been noted for this type of irrigated agriculture. Irrigated area in each country (as a percentage of cultivated area) is shown in Figure 1.1.

Table 1.3. Top 10 irrigated countries in the world in 2017 (adapted from FAO, 2021).

Country	Irrigated Area (millions of acres)	Population (millions)
India	174	1,339
China	173	1,453
United States	66	325
Pakistan	49	208
Iran	22	81
Indonesia	17	265
Thailand	16	69
Mexico	16	125
Turkey	13	81
Brazil	11	208

At the beginning of the twentieth century, irrigation in the western United States amounted to about 3 million acres. Early Caucasian settlers in the western United States were no different than people of ancient civilizations. They developed cooperative irrigation practices and formed communities, especially in southern California and Utah. Irrigation development in the west in the twentieth century was tied closely to the 1902 Reclamation Act which provided capital and the expertise to construct major water supply facilities. During the first three decades of the twentieth century, large multipurpose federal water projects were designed and built for irrigation, flood control, power generation, wildlife and fish habitat, and water-based recreation. Examples include the Colorado River, the Columbia Basin, Central Utah, the Missouri Basin, the Minakoka Project of Idaho, and the Salt River Project of Arizona. Following these projects, private development of pump irrigation from extensive natural underground reservoirs (aquifers) in the plains states, ranging from the Dakotas south to the high plains of Texas, permitted a major increase in irrigation from 1950 to 1980. In the last decades of the twentieth century, irrigation in southeastern states like Florida, Georgia, and South Carolina, where crops grown extensively on sandy soils are at risk during periods of drought, increased rapidly.

The distribution of irrigation in 2017 in the United States from the USDA Farm and Ranch Irrigation Survey is shown in Figure 1.2. The irrigated areas of 20 leading states are presented in Table 1.4, as well as the percentage change in irrigated area for these states over a 15-year period (2002 to 2017). The data for several western states, like California, Arizona, Wyoming,

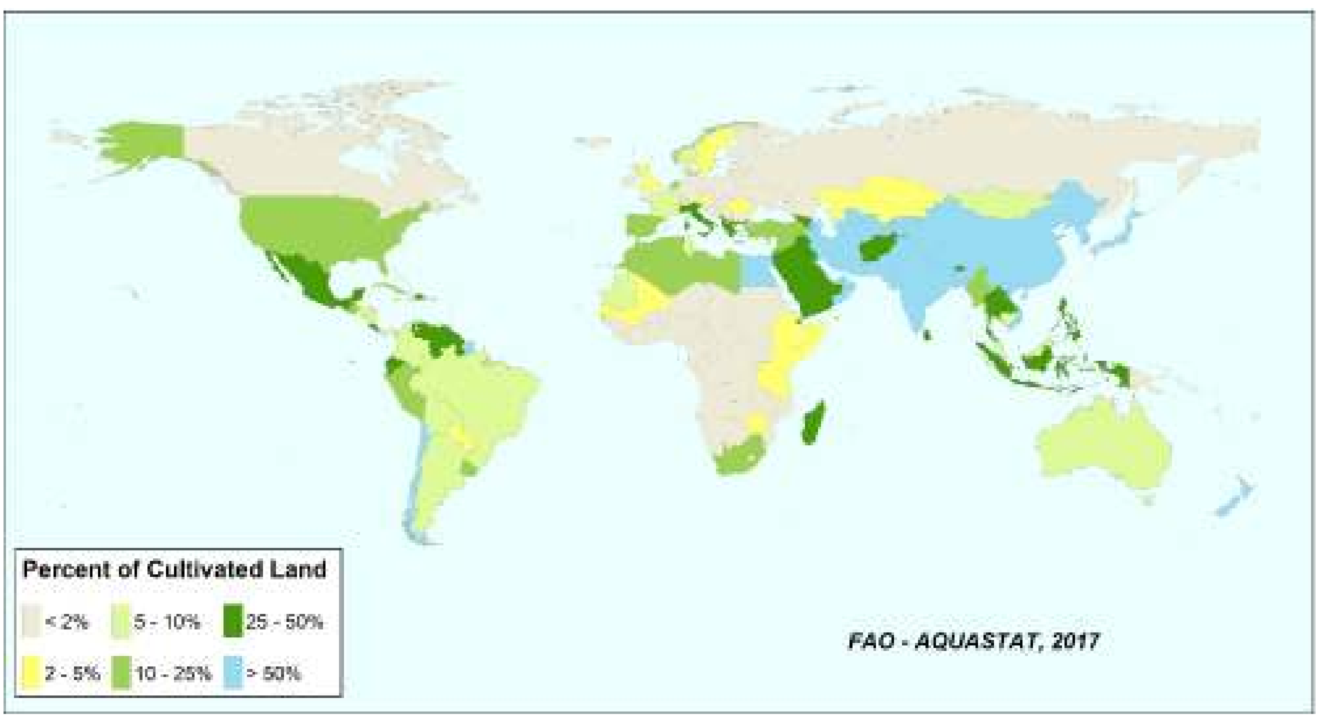

Figure 1.1. Global distribution of irrigation as a fraction of cultivated land area. Data from FAO (2021).

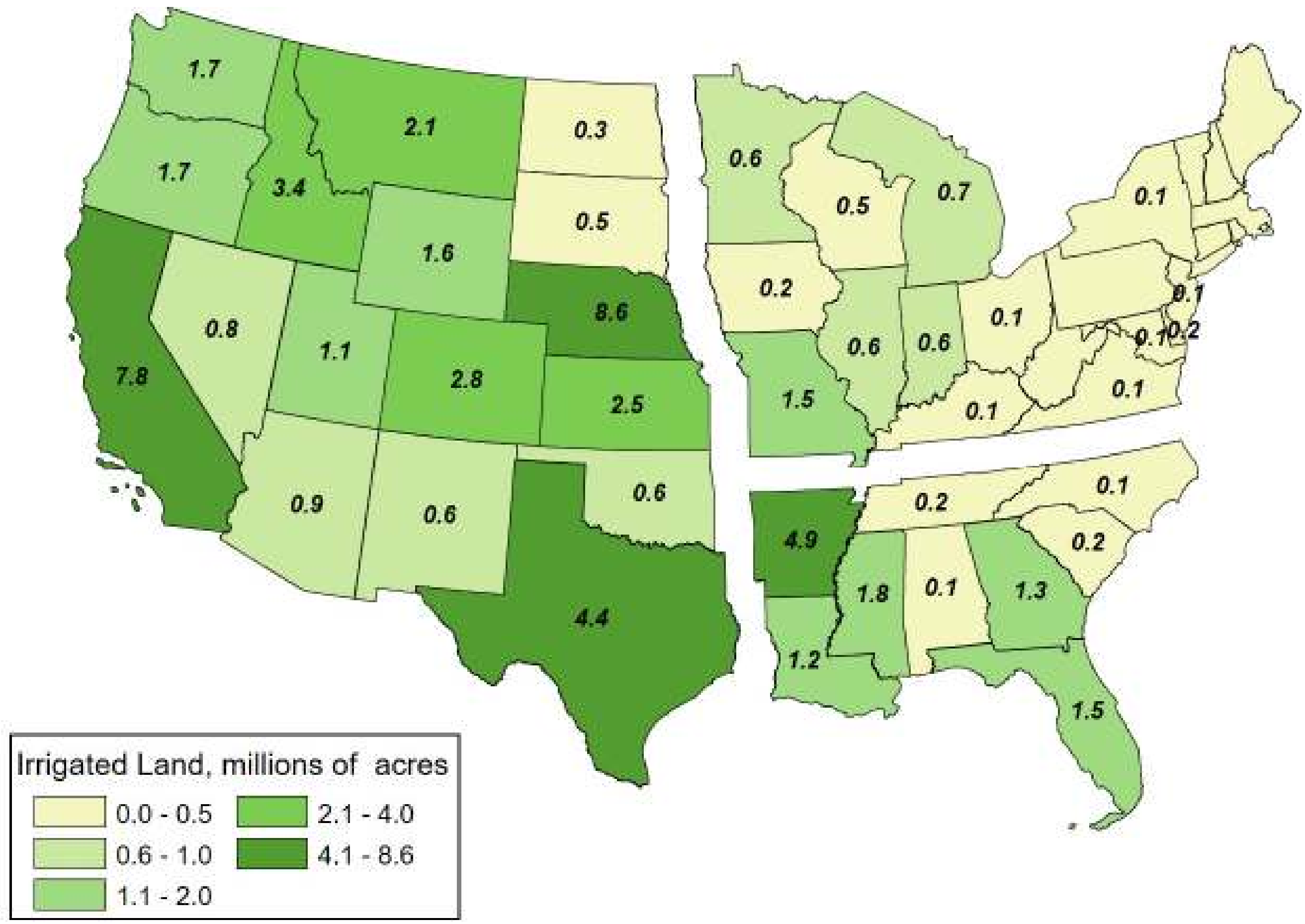

Figure 1.2. Irrigated farmland by state in the United States in 2017 (data from USDA, 2019).

Colorado, Montana, Idaho, Texas, and Utah, indicate that the size of the irrigated area either increased slowly or decreased. This indicates that land and water resources were developed near the maximum possible area under the socioeconomic conditions of the time. Areas with large increases in irrigation were near or just east of the hundredth meridian, the line on the globe that roughly divides the semiarid West from the subhumid Midwest in the United States. The states of Arkansas, Georgia, Louisiana, Michigan, Mississippi, Missouri, and Nebraska had large percentage increases in irrigation during the 15-year period. This increase, in large part, was a consequence of groundwater being tapped by irrigation wells. As you review the 20 leading irrigation states, you will also notice the amount of irrigated lands in southeastern states, like Georgia, Mississippi, and Louisiana, increased dramatically during the 15-year period. By 2017 there were over 58 million irrigated acres in the United States (Table 1.4).

The type of irrigation system (Chapter 5) in the United States has also changed with time. Table 1.5 summarizes the percent of irrigated land using surface, sprinkler, and microirrigation since 1950. After a maximum of 98% surface irrigation (Chapter 10), this type of irrigation system has declined to 35% of the irrigated area in 2018. Meanwhile, the amount of sprinkled land has increased from 2%of the irrigated land in 1950 to 55% 2018. The amount of sprinkle irrigation (Chapters 11-13) now surpasses that of surface irrigation in the U.S. Microirrigation (Chapter 14), which includes drip/trickle, microspray, and similar systems, has increased from its infancy in the 1960s to 3 million acres at the turn of the century. Microirrigation accounted for 10% of the irrigated area in the U.S. in 2018.

Table 1.4. Irrigated land in the United States in 2017 and the percent change over the previous 15 years. The 20 leading irrigation states are listed along with data by region and nationally (adapted from USDA, 2014, 2019).

	Irrigated Land (acres)	Percent Change Since 2002
State:		
Arizona	911,000	-2
Arkansas	4,855,000	17
California	7,834,000	-10
Colorado	2,761,000	7
Florida	1,519,000	-16
Georgia	1,288,000	48
Idaho	3,398,000	3
Kansas	2,503,000	-7
Louisiana	1,236,000	32
Michigan	670,000	47
Mississippi	1,815,000	54
Missouri	1,529,000	48
Montana	2,061,000	4
Nebraska	8,588,000	13
Nevada	790,000	6
Oregon	1,665,000	-13
Texas	4,363,000	-14
Utah	1,097,000	1
Washington	1,689,000	-7
Wyoming	1,568,000	2
Region:		
19 Western states	41,234,000	-2
9 Southeastern states	11,393,000	20
22 Northeastern states	5,387,000	41
Nation:		
U.S. total	58,014,000	5

Table 1.5. Comparisons among irrigation methods in the United States since 1950 (adapted from Irrigation Journal, 1971, 2000, 2001; USDA, 2014, 2019).

Year	Irrigation Method		
	Surface	Sprinkler	Microirrigation
	(percent of total irrigated area in U.S.)		
1950	98	2	-
1970	81	19	-
1990	56	42	2
2000	45	50	5
2008	39	54	7
2018	35	55	10

1.4 Impact of Irrigation on Water Resources and the Environment

As responsible stewards of our natural resources, irrigation managers should consider any negative impacts from irrigation along with the benefits of irrigation. Irrigation may have a negative impact on water quantity and/or water quality. Surface water diversion for irrigation will result in reduced streamflow downstream and reduced water volume in downstream water bodies. The Aral Sea, between Uzbekistan and Kazakhstan, is an extreme example, now being less than 10% of its original size. Irrigation from groundwater pumping will result in declining groundwater levels and stream flow depletion if annual pumping exceeds the annual groundwater recharge (Figure 1.3). Reduced groundwater levels may result in reduced baseflow in nearby streams (Chapter 9). Crop water use (Chapter 4) is often the largest use of water in agricultural watersheds. It is important for water resources managers to understand that reductions in water diversions for irrigation do not always result in a reduction in consumptive use of water resources (Chapter 5).

Water quality concerns include both groundwater and surface water. Irrigation often results in deep percolation, resulting in the leaching of soluble fertilizers or other chemicals (Chapter 5). In some areas, nitrate leaching has resulted in groundwater nitrate concentrations above the maximum concentration allowed for human consumption. Deep percolation can be minimized with good irrigation scheduling (Chapter 6). Runoff from irrigation can contain nutrients, pesticides, and sediments. This can particularly be a problem in surface irrigation systems where the runoff is collected and reused on additional fields (Chapter 10). Chemigation needs to be managed well to prevent chemical application on surface water bodies or groundwater contamination through backflow from the irrigation system (Chapter 15).

Finally, soil quality is also a concern. Irrigation systems that result in runoff may also trigger soil erosion. In arid regions, salt accumulation in the soil can be a significant concern

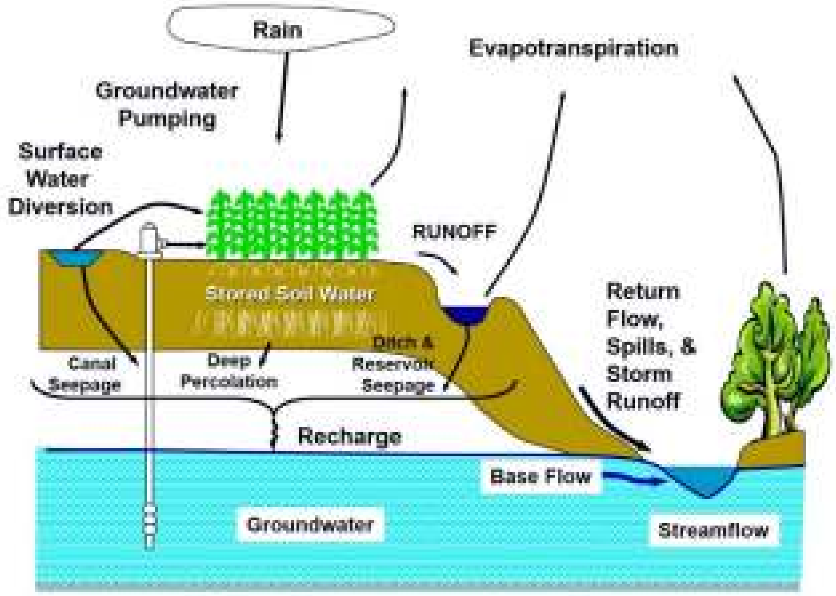

Figure 1.3. Large-scale water balance, showing the water cycle and interactions between irrigation and surface and groundwater resources.

depending on the salinity of the irrigation water (Chapter 7). In these situations, it is often necessary to include subsurface drainage along with the irrigation system.

Good irrigation management should seek to increase food production (and farm profits) while minimizing negative impacts on water resources and the environment. In many situations, best management practices provide methods to achieve both of these goals simultaneously.

1.5 Irrigation Management Concepts

Modern irrigation management is based on the concept of soil-plant-water relations. This concept is a unification system in which all processes are interdependent. In this unified system, called the soil-plant-atmosphere relations, the availability of soil water is not a property of the soil alone, but a function of the plant, soil, and environment. The rate of water uptake by the plant depends on the root's ability to absorb water from the soil, the soil's ability to transmit water toward the roots, and the evaporative demand of the atmosphere. These, in turn, depend on: (1) characteristics of the plant such as rooting density, rooting depth, rate of root growth, and the plant's ability to maintain its vital functions under water stress; (2) properties of the soil like hydraulic conductivity, soil bulk density, soil texture, soil layers, water retention, and available water capacity; and (3) weather conditions which dictate the rate of transpiration from the crop and soil evaporation. These components of the continuum will be presented and discussed for soil water (Chapter 2) and plant water use (Chapter 3).

Irrigation scheduling is the term that describes the procedure by which an irrigator determines the timing and quantity of water application. It is possible to schedule irrigations based on monitoring the soil, the plant, and/or the microclimate. By monitoring soil moisture, the idea is to measure the reserve of water within the crop root zone as it is diminished following each irrigation to ascertain when the soil water has been depleted to a prescribed minimum level. Sensing the water status of the plant is a second method to detect the beginning of plant water stress. There are many plant sensing techniques available today to measure or infer plant water status ranging from specialized equipment to visual observation. As important as the earliest detection of plant water stress is, it does not give information on how much water to apply. A third technique is to monitor the meteorological conditions that impose the evapotranspirational demand on the crop. Accumulating the amount of water lost to the atmosphere by the crop will estimate the amount of water to apply. The timing of the irrigation is established by knowing the capacity of the soil to store water or monitoring the water status of the plant. These various measuring techniques and strategies for scheduling irrigations will be presented in detail (Chapter 6).

The later chapters of the text are devoted to descriptions of the various types of irrigation systems, emphasizing the major methods employed in irrigated agriculture (Chapters 10-14). The application of agricultural chemicals through irrigation systems is presented separately (Chapter 15). Effective management of irrigation systems also benefits from a working knowledge of the hydraulics of pipeline and pumping systems (Chapter 8).

1.6 Summary

Irrigation is extremely important in the production of food, other agricultural products, ornamentals, and turf. One-third of the world's food is produced on the 21% of the world's cultivated area that is irrigated. In the U.S., about 50% of the total value of all crop sales comes from the 28% of the cropland that is irrigated. Thus, the understanding of irrigation and its management are critical to all of us.

Here, the basic concepts to understand are that water is applied, distributed in the soil, and stored for plant use. Various irrigation systems and their operation and management are then presented in the context of each system's advantages and disadvantages. Procedures for determining when and how much irrigation water to apply are discussed in detail throughout this text to assist the reader in being as efficient as possible when utilizing this precious resource, water.

Questions

1. Name the three states west of the Mississippi River with the largest irrigated areas.
2. Name the three leading states east of the Mississippi River with the largest irrigated areas.
3. Which state lost the largest amount of irrigated land from 1969 to 1999?
4. Which state gained the most acres of irrigated land?
5. Name three states where microirrigation is a popular irrigation method. Where is sprinkler irrigation practiced and why?
6. List three benefits and three negative consequences from irrigation development.
7. Explain why the irrigation industry is changing from a development era to a management era.

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