CHAPTER 2

SUSTAINABLE AND PRODUCTIVE IRRIGATED AGRICULTURE

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Abstract. *A renewable water supply is required for sustained irrigated agriculture. Irrigated agriculture can remain productive indefinitely with assurance of water supplies and infrastructure to deliver water as needed for crop production. Emerging issues facing designers of irrigation systems are competition for limited and declining water resources, climate variability, effects of leasing water during drought years on annualized water costs, environmental concerns, refined irrigation scheduling, and drainage and salinity control issues. Designers of irrigation systems must consider the role of irrigation in food production, and the productivity of water used for irrigation.*

Keywords. *Climate-based irrigation scheduling, Deficit irrigation, Design challenges, Environmental concerns, Sustainable development, Water, Water accounting.*

2.1 INTRODUCTION

2.1.1 Scope of the Chapter

Since the first edition of this monograph (printed in 1980), numerous papers and books have been published on irrigation systems and practices, trends in food production, climate and water requirements, irrigation experiences in arid, semiarid, subhumid, and humid areas, and various beneficial uses of irrigation water. Some of these subjects are covered in detail in other chapters. This chapter highlights recent trends and emerging issues facing designers and operators of farm irrigation systems. Sustainable irrigated agriculture depends on a renewable source of water and adequate drainage for control of soil salinity. Increasing competition for limited water supplies will require increasing attention to the water productivity, i.e., the production of the marketable component of a crop per unit of water consumed. *Water consumed* is that fraction of water applied that is evaporated, transpired, or combined within the crop and is no longer available for other uses. The fraction of water applied that is not consumed, i.e., irrigation return flows, and other environmental concerns will need to be addressed by designers of irrigation systems. Maximizing crop yields will no longer be the main objective of irrigation; more attention will be on maximizing *net* benefits of irrigation.

2.1.2 Water, Plant Growth, Irrigation, and Crop Production

Water is essential for plant growth. Seeds need water to germinate, most soils must be moist for seedlings to emerge, and many plant growth functions require water. Water provides the transport mechanism within plants for nutrients and products of photosynthesis. However, most of the water consumed by plants is by transpiration, a process that is controlled by climate and leaf area when soil water is not limiting. The combined processes of evaporation from the soil and plant surfaces and transpiration is called *evapotranspiration (ET)*. Procedures for estimating ET are given in Chapter 8.

Irrigation supplements precipitation by providing water essential for plant growth, in addition to controlling soil salinity and enhancing the root environment. The impact of irrigation on crop yields is greatest in arid and semiarid climates and in humid and subhumid climates during drought years. Irrigated crop yields are higher and more stable than yields on adjacent dryland areas (often referred to as *rainfed* areas). National famines, once common, have been avoided because of irrigation. Irrigation was a major factor in the success of the Green Revolution and will become even more important in the future to provide food for the ever-increasing world population. Stability of crop production under irrigation also provides economic stability to independent farmers and to communities. Without irrigation, increases in agricultural yields and outputs that have fed the world's growing population would not have been possible. Irrigation has also stabilized food production and prices (Rosegrant et al., 2002).

Irrigation is also used for many secondary purposes. For example, it is used to control frosts in orchards and citrus groves, and to condition the soil when preparing seedbeds and harvesting root crops such as potatoes, sugar beets, and peanuts (see Section 2.6). More recently, irrigation has become a common and environmentally acceptable method of making economic use of waste effluents for crop production. Previously, most of these effluents were merely disposed of in some manner, such as being discharged to rivers and streams, evaporated in holding ponds, or applied to nonproductive vegetation to accelerate the evaporation process.

2.1.3 Sustainable Irrigated Agriculture

During the past decade, many authors have addressed the issue of sustainable development and sustainable agriculture and agricultural systems (Edwards et al., 1990; Hatfield and Karlen, 1993). Their publications address issues of soil fertility, crop and pest management, soil erosion, soil salinity, waterlogging, economics, environment and water quality, bioresources, ecology, policy, sociology, and socioeconomic issues. The quantity of renewable water resources, which is the most vital component of sustainable irrigated agriculture, has been addressed to a limited extent. Sustainable crop production on irrigated lands will require a sustainable and renewable water supply. Seckler et al. (1998) prepared a comprehensive analysis of global water demand and supply from 1990 to 2025. A water balance approach was used to derive estimates of water supply and demand for individual countries and regions and to identify major regions of water scarcity. During an international conference on sustainability of irrigated agriculture, various views of on-farm water management, water quality, and capacity building were discussed along with country and regional concerns in Africa, Asia, and China (Pereira et al., 1996).

The Council for Agricultural Science and Technology (CAST, 1992) addressed the impacts of climate change on U.S. agriculture and the limitations of renewable water resources on adapting to climate change. A committee of the Board of Water Science and Technology of the National Research Council (NRC) conducted a thorough study of the future of U.S. irrigated agriculture (NRC, 1996). The Committee reported that the availability of water has been, and is likely to remain, the principal determinant of the status of irrigation in the western U.S. The availability of water is becoming increasingly important to irrigation in eastern states as well. The cost of water and demands on water resources are increasing.

In 1989, the Food and Agriculture Organization (FAO) of the United Nations developed an international action program for the 1990s on water and sustainable agricultural development (FAO, 1989). It emphasized the need for long-term strategies consistent with limited water resources and competing demands for water. The NRC Committee on International Soil and Water Research and Development stated that one of the challenges we face in developing agricultural strategies that is truly sustainable is maintaining the resource base, the soil and water resources that make agriculture possible (NRC, 1993).

Globally, the largest threat to sustainable irrigated agriculture has been, and still is, waterlogging and soil salinity. During the three decades from 1960 to 1990, the world witnessed a historic expansion of irrigated land. During this period, irrigated agriculture played a major role in increasing food production. Currently, an estimated 36% to 47% of the world's food is produced under irrigation (Chapter 1). During the rapid expansion, some principles of irrigation design, operation and maintenance, and water balance appear to have been compromised resulting in waterlogging and soil salinity. Soils become waterlogged if water is imported in addition to precipitation in excess of crop ET and adequate drainage is not provided to remove the excess. Increases in soil salinity usually follow waterlogging because salts present in irrigation water become concentrated near the soil surface as evaporation from the soil removes pure water (see Chapter 7).

In some developing countries, the continuing availability of relatively low cost energy may be a serious restraint on converting common surface irrigation systems to modern, more efficient systems that require more energy input. Thus, energy required for irrigation could also become a factor affecting the sustainability of irrigated agriculture.

2.1.4 Productive Irrigated Agriculture

Some societies have practiced irrigation for centuries without adverse soil and environmental effects. In general, irrigated agriculture can remain productive indefinitely if a reasonably stable renewable water supply of suitable quality is available and the volume of applied water does not exceed ET and the drainage capacity, so that soils are not waterlogged. Perry (2002), referring to countries that have developed and controlled their water resources for decades and centuries, listed the essential elements of sustained water resources management as: knowledge of resource availability, governing policies, assigned priorities for developed water among users, allocation rules and procedures, defined roles and responsibilities, and infrastructure to deliver the service to each water user.

In regions where water is scarce, agriculture may need to temporarily relinquish some water supplies in drought years to provide for domestic and other higher value water uses. This has become common practice in some areas of the western U.S. and will become a more common practice internationally. This practice may not change the productivity of the irrigated land in a given year, but will affect long-term mean production potential from an area because not all lands will be irrigated fully each year. Lands not fully irrigated may be planted to a crop and some crops may not be irrigated for near maximum yields.

In addition to water, other inputs are needed to maintain productive irrigated agriculture. When irrigation removes the main constraint affecting crop yields (water), then other factors such as plant nutrition and changes in soil salinity may limit crop production.

2.1.5 Emerging Issues Facing Designers

Designers of farm irrigation systems in the 21st century face many new challenges. Competition for limited water supplies will require irrigators to have greater control of the amount and uniformity at which the water is applied over the fields. Typically, this will increase the costs of new or modernized irrigation systems. Future renewable water supplies may not be as dependable as they have been in the past. For example, in parts of the Great Plains farmers are faced with decreasing flow rates from wells as the water table is lowered in the vast Ogallala aquifer. This aquifer has very limited natural recharge over much of its surface area. If a farmer already has an operating well on the farm, the efficiency of the pump will decline as the water table drops and the flow rate decreases. Farmers must consider the potential return on investments required to modernize and replace the pump and existing irrigation systems with more modern and efficient systems. The alternative is to return to dryland farming. The irrigation system designer must take into account the effects of decreasing flow rates and limited water supplies on irrigation system efficiencies. Particularly in regions like these, long-term planning is necessary and designers need to consider long-term returns, not just irrigation to meet the component of ET that is not not provided by precipitation or the consumptive irrigation requirements.

The farmer also must consider alternative management practices to cope with the relatively large variation in seasonal precipitation in semiarid areas. Studies in the High Plains of Texas have shown that in most years, limited irrigation of drought-tolerant crops can significantly increase yields and the productivity of water applied. In years of above-average rainfall, irrigation may be of limited benefit. For example, a three-year study in Kansas showed that when precipitation was about 30% above normal (during 1989 and 1990), there was no benefit from irrigating grain sorghum [*Sorghum bicolor* (L.) Moench]. During the following year (1991), precipitation was below normal, and sorghum and wheat yields as well as water use efficiency (WUE) were higher in irrigated treatments than on dryland treatments (Norwood, 1995). WUE is commonly defined as the marketable product produced per unit of water consumed in ET. In 1991 (the year with below normal precipitation) WUE tended to be greatest from the first increment of irrigation water applied. This example illustrates how weather variables can complicate the design of an optimal irrigation system in semiarid areas.

Western U.S. water rights have long protected investments in irrigation facilities. But water laws are changing making it easier for farmers to sell the *consumptive use* (CU) component of their water right to users who are willing to pay more for the water than the farmer's profit potential from irrigation. If some farmers within a project or district sell their entire CU rights rather than lease it for a season, the cost of operation and maintenance of the district's main distribution system will be distributed to the remaining farmers who continue to irrigate. Where this situation occurs or is expected to occur, designers need to give the farmer information about the alternatives of modernizing a system, rather than maintaining the present system, and also about the options of selling the water right and terminating irrigated farming operations. More commonly, farmers are leasing their water during water-short years through various mechanisms (NRC, 1992). Under these conditions, an irrigation system may not be used each year, which will also affect annualized system costs.

Distributing fertilizers and pesticides in irrigation water (chemigation) has become commonplace and can be very efficient. Chemigation requires new design considerations compared with traditional systems. In addition, new environmental concerns and associated regulations affecting return flows to streams or to the groundwater are becoming significant factors that the designer must consider.

Many states have installed automated weather stations to measure and disseminate estimates of evaporative demand or crop ET. Use of such data by irrigation managers to schedule irrigations can enhance the productivity and efficient use of water resources (Ley, 1995). Designers of modern irrigation systems must consider that, in the future, most farmers will become dependent on real-time estimates of ET and soil water depletion when scheduling their irrigations and determining the amounts that should be applied. The designer needs to consider simulating multiple years of operation based on estimated daily ET using procedures described in Chapter 8. For high-value crops, many new irrigation systems will be automated with irrigations initiated using soil water sensors, computed depletion of soil water, or remote sensing techniques.

2.2 ROLE OF IRRIGATION IN FOOD AND FIBER PRODUCTION

2.2.1 Population Growth and Renewable Water Supplies

World population growth and irrigation are related, i.e., an increasing population requires increased irrigation. World population is increasing about 1.2% per year (Population Reference Bureau, 2005); it was about 5.3 billion in the early 1990s and increasing at a rate of 93 million people per year. The U.N. Population Division suggested that the global population will increase to 9.3 billion by 2050. With the increased population comes increased food needs.

Thus, population growth and its effects on water supplies and food requirements is a variable that must be considered by irrigation system designers and operators, particularly in many developing countries. In the U.S., population growth probably will not be significant in the near future. However, hotspots of water scarcity occur in the Colorado, Rio Grande, and Texas Gulf basins (Rosegrant et al., 2002). Irrigation designers must consider planning at a regional scale and be aware of current regional plans and expected new regulations in order to properly design irrigation systems. Rosegrant et al. (2002) provided a useful table of 1995 and projected 2025 populations by country and region using data from several sources.

The world annual per capita internal (i.e., within a country) renewable water supply is about 7000 m^3, but this varies greatly between regions. For instance, in the Middle East and North Africa, the International Bank for Reconstruction and Development (IBRD) estimates the per capita water supply to be only about 1000 m^3 (IBRD, 1992b). Renewable water supplies are finite and can essentially be considered as a constant within a region. The rate of population growth is often very high in regions that already have some of the lowest per capita water supplies. For example, the weighted average rate of increase in population in the Middle East in the late 1980s was 2.7% per year (Jensen, 1990). In that region, the per capita water supply, which is already low, would be expected to decrease to half its present value in just 26 years. The estimated 2005 population in this region was 47% higher than in 1989 (Population Reference Bureau, 2005). The weighted average annual rate of increase in 2005 had decreased slightly to 2.2%.

2.2.2 Increasing Food Demands Relative to Water Supplies

As populations increase, competition among agricultural and non-agricultural water uses will affect irrigated agriculture in many semiarid and arid areas. These pressures will become more severe as water supplies are more fully utilized. Conflicts will increase. Solutions to these conflicts will require revisions of water law and allocations. Australian scientists, for example, are proposing a landmark national water trading framework to define water rights for irrigation. This water rights system would be based on banking, share trading, and Torrens Title registration procedures which would allow water to be traded via electronic transfers with licensed brokers and clear trading rules. The system would have three components: an entitlement, an allocation, and a use license (CSIRO, 2002). The authors claim that the advantage of this system is that it would provide flexible control as climate, economic, and technical circumstances vary.

In the future, the price of water will be more closely related to its real economic cost. This will affect irrigated agriculture because the current value of the marketable product of some crops per unit volume of water consumed is low. For example, only about 2 kg of maize grain valued at about $0.20 can be produced in arid and semiarid areas per cubic meter of water consumed in ET. For many semiarid and arid areas, it will not be economical to import and use a cubic meter of water (= 1 ton of water) to produce 2 kg of grain even if a renewable source of water was available. These areas will be forced to use local water for domestic purposes and to import more feed and food supplies (Jensen, 1993). Importing grain rather than importing water to produce grain locally is sometimes referred to as importing *virtual water*. Where agriculture has been the primary source of foreign currency, depending on virtual water may require generating foreign currency from other sources.

Few irrigation projects are planned to supplement dryland agriculture in semiarid areas. However, limited irrigation can significantly increase the production per unit of precipitation and stored soil water consumed by ET. For example, in the High Plains of Texas, dryland grain sorghum produces from 0.45 to 0.85 kg/m^3 of water with yields from 1000 to 3000 kg/ha. Limited irrigation can increase yields to about 5000 kg/ha and average productivity to about 1.2 kg/m^3 (Jensen, 1984). The first 100-mm increment of irrigation water had the most effect by increasing the yield from 2500 to 4000 kg/ha. The productivity of this increment of irrigation water would be 1.5 kg/m^3. This is an example of the future role for irrigation in semiarid areas, especially where renewable groundwater supplies are available. Irrigation development must be integrated *with* dryland production rather than planned, developed, and managed as a competitive enterprise (Jensen, 1993).

2.2.3 Downstream Environmental Effects

Downstream environmental effects may include reductions in wetlands and lakes as crops consume water that formerly flowed to lakes and wetlands. One dramatic example is in the former Soviet Union. In 1918, the Soviet Union decided to become self-sufficient in cotton. To irrigate cotton fields, they began diverting 55 km^3 of water per year from two rivers that feed the Aral Sea (Sun, 1988). Over the years, little water reached the Aral Sea and it has shrunk drastically in size. Huge salt storms have carried salt from the shores of the shrinking basin great distances, damaging agricultural lands (Ellis, 1990; Micklin, 1988). The ICID organized a special session on the Aral Sea Basin in 1994 (ICID, 1994), a NATO-sponsored workshop was held on this issue in Wageningen, The Netherlands, in 1995, and the World Bank has established an independent advisory panel to provide guidance to the Bank on managerial and technical issues of this problem. However, the Aral Sea problem still exists. The river system has been encroached upon by bridges, etc., so that even if irrigation diversions ceased, the increased flow could not reach the Sea. In hindsight, a better approach would have been to balance the water requirements for irrigation against the inevitable reduction in the flow to the Aral Sea and the resulting environmental consequences. Heaven et al. (2002), using a real-time mass balance river/reservoir model for Syr Dara (one of the rivers), concluded that water is either being used extremely inefficiently, or river offtake data or cropped area data are unreliable, or both.

Water is still being diverted for irrigation. The river system has been encroached upon by bridges etc. so that even if diversions ceased, the increased flow could not reach the Sea. A great misconception still exists that by increasing irrigation efficiency, there would be more water for the Sea. "Irrigation efficiency" is the fraction of water consumed.

On a much smaller scale in the U.S., the diversion of water from the Truckee River in 1902 lowered Pyramid Lake in Nevada about 24 m during the following 80 years. Although reallocation of water supplies appears to have stabilized the lake, the large, deep freshwater lake, which used to overflow periodically into Winnemucca Lake, has become slightly more saline (Jensen, 1993).

2.2.4 Water Quality Aspects

A major external effect of irrigation is the dissolved solids in return flows. ET concentrates the salt that is in applied water. This decrease in water quality is inevitable with removal of pure water by any consumptive water use, not just agriculture. This is an environmental cost that represents a trade-off between allowing water to flow in streams to sustain instream environmental benefits versus offstream beneficial consumptive uses. In the future, more regulations or compromises mutually agreed upon by users and regulators can be expected.

Some fertilizer, mainly nitrogen, is added to the return flow downstream from irrigated areas by leaching. Better nutrient and irrigation management, however, can limit the impact of this problem. For example, Ferguson et al. (1990) showed that both irrigation and fertilizer management influenced the amount of nitrate-nitrogen leached. They showed that the potential reduction in fertilizer costs by using irrigation scheduling, soil testing, and fertilizer management services could be profitable. Studies in other areas have shown similar results. Application of excess plant nutrients and ineffective water management will continue until the real cost of water pollution is paid for by the polluters or regulations are implemented. Pesticide residues have also been found in return flows; these can be likewise prevented or reduced to minimal and safe levels by improved management practices.

Irrigation in some arid areas with complex geology can affect the quality of water flowing to downstream wildlife areas. For example, Lico (1992) reported drainage to wildlife areas in west-central Nevada showed high concentrations of potentially toxic arsenic, boron, lithium, molybdenum, un-ionized ammonia, uranium, and vanadium. Several such investigations by the U.S. Geologic Survey have been completed. A committee commissioned by the Water Science and Technology Board of the U.S. National Research Council analyzed irrigation-induced selenium contamination and irrigation-related drainage problems associated with the Kesterson Reservoir in California (National Research Council, 1989). In that case, the reservoir captured drainage water that originally was intended to drain to the San Francisco Bay area.

Another potential harmful effect of poorly managed irrigation is spreading human diseases: schistosomiasis (bilharzia), dengue and dengue hemorrhagic fever, liver fluke, filariasis, onchocerciasis (river blindness), malaria, Japanese encephalitis, and diarrhea. Schistosomiasis is most closely linked to irrigation. Available guidelines for policy makers, planners and managers forecast vector-borne diseases and help incorporate safeguards into irrigation projects (Birley, 1989, and Tiffen, 1989).

2.2.5 Irrigation Status and Trends

The area of land irrigated in the U.S. increased from the mid-1940s until the 1980s (Figure 2.1), and is continuing to increase in some regions. In the Great Plains, depletion of groundwater and some governmental programs caused the decline in irrigated land area during the early 1980s, mainly in the High Plains of Texas. Increased irrigation mainly in Nebraska and in Texas increased the total in 1997 and 2002 to about that in 1978. (Some apparent changes in the 1980s are due to changed statistical procedures.)

Irrigation expanded rapidly in the Texas High Plains during the drought years of the 1950s. Excellent soils, topography well-suited for surface irrigation without any land leveling, and a good quality, easily accessible water source enabled rapid irrigation expansion. The well-known Ogallala aquifer was the main source of water. However, its natural recharge rate in the area was very low and groundwater levels dropped rapidly during the next 20 years. As a result, well flow rates decreased drastically and pumping costs increased due to larger pumping lifts and higher fuel costs. Some lands put under irrigation in the 1950s and 1960s have been returned to dryland farming. Recently, most surface irrigation systems have been replaced by center pivot (CP) sprinkler systems because center pivots can apply water uniformly with smaller flow rates. Also, less water needs to be pumped because with CP systems there is usually little or no runoff and less than full irrigation (deficit irrigation) can be achieved.

In Florida, farmers irrigate a high percentage of cropped land because of very sandy soils and the need for quality control of high-value crops even though annual rainfall is about 1270 mm. Florida growers have converted many sprinkler systems to microirrigation systems. In citrus groves, microsprinklers are designed to cover the citrus trunks for freeze control (Parsons and Wheaton, 1995). Irrigated lands have also increased steadily in other eastern states since 1978 (Figure 2.2). These include the north-central states of Michigan, Minnesota, and Wisconsin where sandy soil has been a major factor influencing expansion of irrigated lands. In these states, groundwater has been the main source of water. Without a convenient and renewable source of water, farmers do not irrigate, even though potential increases in crop yields would offset

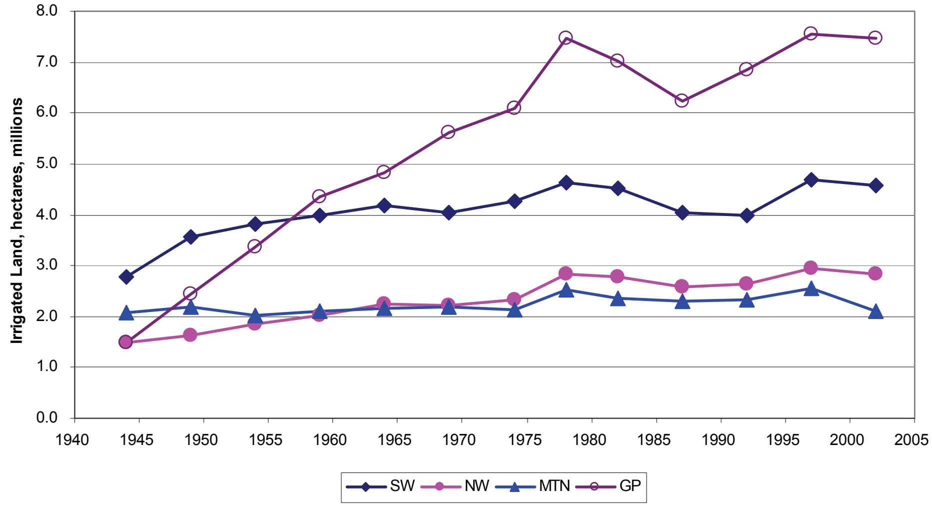

Figure 2.1. Expansion of irrigated land from 1944 to 2002 in the western U.S. SW = Southwest (Arizona, California, New Mexico, Nevada); NW = Northwest (Idaho, Oregon, Washington); MTN = Mountain States (Colorado, Utah, Wyoming); and GP = Great Plains (Kansas, Nebraska, Montana, North Dakota, Oklahoma, South Dakota, Texas). Source: USDA 1997 and 2002 Censuses of Agriculture (USDA-NASS 1999, 2004).

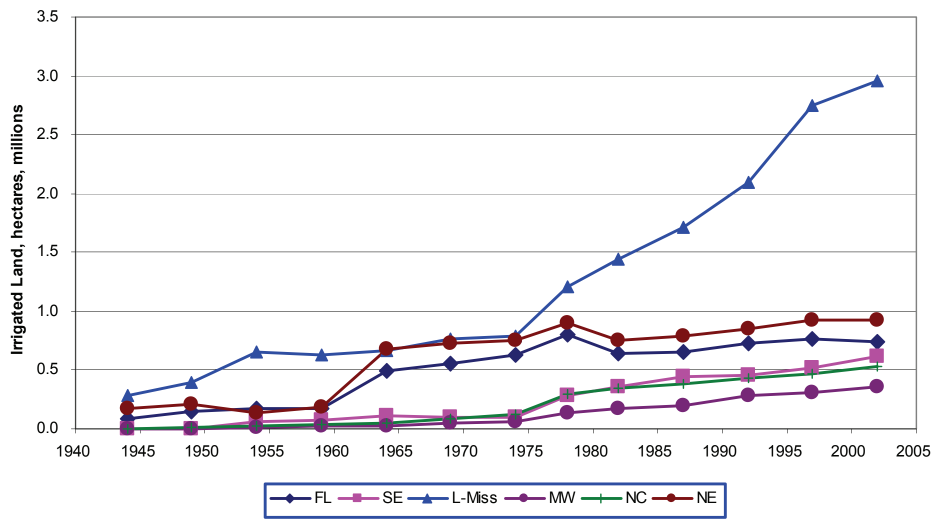

Figure 2.2. Expansion of irrigated lands from 1978 to 2002 in the eastern U.S. FL = Florida; SE = Southeast (Alabama, Georgia, Kentucky, North Carolina, South Carolina, Tennessee, Virginia); L-Miss = Lower Mississippi (Arkansas, Louisiana, Mississippi, Missouri); NC = North-Central (Michigan, Minnesota, Wisconsin); and NE = 12 remaining northeast states. Source: USDA 1997 and 2002 Censuses of Agriculture (USDA-NASS 1999, 2004).

capital and operating irrigation costs, especially in drought years. Irrigated land in the lower Mississippi states of Arkansas, Louisiana, Mississippi, and Missouri has increased markedly since 1978. Over half of the irrigated land in the lower Mississippi region is in Arkansas. Conflicts over water have developed in the southeast because of limited groundwater supplies and lack of surface water storage facilities.

The impact of sustainable water supply on the expansion or decrease in irrigated area is readily apparent when considering its recent history in the Great Plains. The area of irrigated land in Texas expanded rapidly until about 1980, and then decreased as groundwater supplies decreased. In contrast, the irrigated area in Nebraska also increased rapidly, especially with the development of the center-pivot sprinkler system in the 1960s, and has continued to increase to 2002 (Figure 2.3). Nebraska's water supply is from both surface and groundwater supplies, which have been relatively stable.

Global statistics on irrigated land area are not as robust as that in a single country because uniform statistical methods are not always used. For example, in some countries cropping intensity is considered, so land that is double cropped within one year may be counted twice. Also, sometimes the area commanded by a canal may be reported instead of the actual land irrigated. The irrigated land reported by FAO appears to be the most consistent and is the basis of the values reported in this section. The rate of increase in irrigated land reached a peak of about 2.2% per year in the mid-1970s (Jensen, 1993). The total arable land irrigated at the beginning of the 21st century was about 275 million hectares. The annual rate of increase has decreased since the mid-1990s to less than 0.5% per year at the beginning of the 21st century (Figure 2.4).

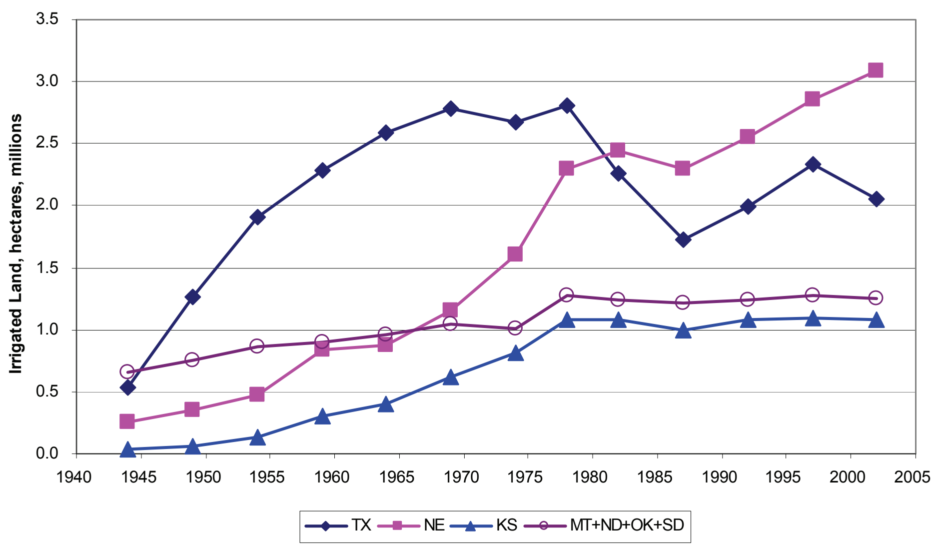

Figure 2.3. Expansion of irrigated land in the U.S. Great Plains regions. TX = Texas; NE = Nebraska; KS = Kansas; and MT = Montana, ND = North Dakota, OK = Oklahoma, SD = South Dakota. Source: USDA 1997 Census of Agriculture (USDA-NASS, 1999).

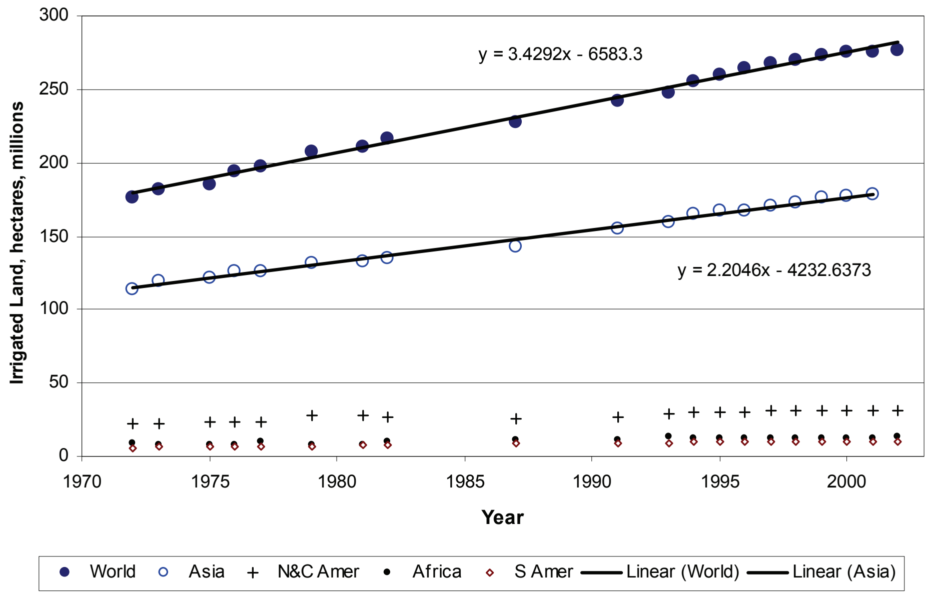

Figure 2.4. Expansion of irrigated land from 1972 to 2002 for the World, Asia, North and Central America, Africa, and South America. Source: FAO Yearbooks and FAOSTAT at www.fao.org.

2.3 CROP PRODUCTION AND IRRIGATION WATER REQUIREMENTS

2.3.1 Crop Production-Evapotranspiration Relationships

When soil water is not adequate for plants to transpire at the climate-based evaporative demand rate, plants experience water stress and plant stomates begin closing to limit transpiration. Since plant stomates also provide for uptake of carbon dioxide, the rate of photosynthesis decreases. Numerous studies have shown that plant growth and crop yields decrease linearly with decreased transpiration.

Since evaporation is only a part of total ET, plant water stress distributed over the growing season also decreases dry matter and marketable yields as ET decreases (Howell, 1990; Howell et al., 1990). Howell (1990) reviewed the results of previous studies and presented a detailed analysis of yield-transpiration and yield-ET relationships for corn, grain sorghum, and winter wheat. The general linear statistical relationship between total ET and yield of cereal grains in a given climate zone is:

$$Y_g = b\,ET + a \tag{2.1}$$

where Y_g = the yield or marketable product, Mg/ha
ET = growing season evapotranspiration, mm
b = the slope of the yield-ET line, Mg/(ha mm)
a = a constant, Mg/ha.

Because some ET occurs before the first increment of marketable product is produced, the value of a is negative. For example, Stewart et al. (1977) reported that for corn yields from several non-saline treatments at Davis, California, in 1974 could be estimated as $Y_g = 0.019\ ET - 1.17$ Mg/ha, i.e., the increase in corn grain per unit increase in ET will be 1.9 kg per cubic meter of water consumed in ET. Values of *b* and *a* will vary with crop cultivars and climate. As new cultivars are developed with higher harvest indices and improved cultural practices, yields may increase with little increase in ET, thereby changing the constants. Climate also will affect the equation constants. With frequent rains when annual plants are small, the evaporation component will be higher than in arid areas. The slope (*b*) may be less in humid areas.

Similar relationships can be developed for dry matter or for forage production. Forage yield-ET relationships from carefully controlled field experiments tend to vary less than grain yields. For example, when using regression data from dryland studies in North Dakota (Bauder et al., 1978), sprinkler-irrigated alfalfa in New Mexico in 1979 (Sammis, 1981), and regression data from studies in Israel (Kipness et al., 1989), the resulting yield of alfalfa at zero moisture could be expressed as $Y_{alf} = 0.015\ ET - 0.50$ Mg/ha, that is, the increase in alfalfa yield per unit of ET will be 1.5 kg/m^3. This value obtained from widely differing climates agrees closely with the seven-year average of well-watered, lysimeter-based yield reported by Wright (1988). Wright reduced the lysimeter yields 5% to agree with adjacent field yields of 1.76 kg/m^3 at 12% moisture, or 1.6 kg/m^3 at zero moisture.

Howell et al. (1990, 2000) also presented detailed analyses of concepts of *water use efficiency* (WUE), which is the the economic or marketable production per unit of water consumed in ET ($WUE = Y/ET$). Bos (1980), working with an ICID group, defined a related term of *irrigation water use efficiency* (WUE_i), which considers the increase in production per unit increase in ET due to irrigation, or $WUE_i = (Y_i - Y_d)/(ET_i - ET_d)$. If there is no dryland yield or ET, the values are the same. Both of these terms have served useful purposes as indices of the effectiveness of various agronomic practices. I have used the WUE terms since the 1950s. However, due to confusion with irrigation efficiency that has often resulted in the literature, I suggested that these terms be considered as indices of the *productivity of water* used in crop production (Jensen, 1993). Either "total water consumed" or "irrigation water consumed" in ET is needed to enable uniform comparisons of practices or between areas.

A comprehensive series of articles on the response of crops to carbon dioxide, temperature, and water quality, and on water shortage, is presented in a publication edited by Kirkham (1999). Chapters on water use by several crops such as cotton, olives, rice, sorghum, sunflowers, turfgrass, and wheat are presented along with a chapter on risk assessment of irrigation requirements of field crops. Stewart and Nielsen (1990) compiled detailed information on irrigation of various crops in a comprehensive monograph.

Relationships between yield and water applied are much more variable than those between yield and ET, because the rainfall during the growing season and the amount of water percolating below the root zone are not the same each year, or from place to place, and will vary with the irrigation method. Even surface runoff may not be taken into account in data reported on water applied and yield. Yield-water application relationships tend to be curvilinear, as shown by Howell et al. (1995) and Letey (1993). Such relationships also tend to be applicable to specific conditions and are not as transferable or as valuable in comparing production practices and systems as WUE parameters. Unger and Howell (1999) presented a global perspective summarizing basic principles and practices for achieving agricultural water conservation, both under dryland (rainfed) and irrigated conditions.

2.3.2 Deficit Irrigation and WUE

A relatively new practice of not replenishing the soil water profile at each irrigation, where rainfall during the growing season is significant, is called *deficit irrigation*. This practice provides soil water storage space for capturing rainfall that otherwise may percolate beyond the root zone. For example, Howell et al. (1995) have shown that when replacing only two-thirds of the depleted soil water at irrigation, the irrigation water use efficiency for irrigation water (WUE_i) for corn increased from 1.8 to 2.3 kg/m^3. WUE_i is defined in Section 2.3.1. The net effect is that a higher proportion of rainfall may be effective with deficit irrigation than with full irrigations.

Another form of deficit irrigation is *managed plant water stress*. For example, when irrigating some small grain cultivars that are subject to lodging, mild plant water stress prior to the boot stage can shorten the stems and increase the resistance to lodging. Terminating irrigation at critical times such as after the soft dough stage of cereals can reduce ET and irrigation water required without a decrease in economic yield. Similarly, on sugar beets, more leaf area may be produced than necessary. Under these conditions, allowing increased plant water stress by limiting irrigations near the end of the season can reduce the mass of beets produced, but increase sugar content. As a result, the total sugar yield may not be affected. A light irrigation before harvest may be required to harvest the beets. A side benefit is that less tonnage needs to be hauled to the sugar factory. Studies on cotton in California showed that irrigations that are too early not only lower final yield of cotton lint, but also result in lower production efficiency (Grimes and El-Zik, 1990). These are examples of how operators of irrigation systems can manage irrigations to reduce water requirements and costs without reducing economic yields. Local experimental data should be used as a guide to manage deficit irrigation. FAO published a Water Report summarizing experiences of deficit irrigation in a number of countries (FAO, 2002). The potential effects of deficit irrigation practices also will need to be considered when designing farm irrigation systems.

2.3.3 Irrigation Requirements for Evapotranspiration and Salinity Control

For design purposes, in most arid areas and especially during the dry part of the season, precipitation has little effect on estimates of irrigation water requirements for ET and salinity control. Methodology for estimating crop ET and irrigation water requirements is presented in Chapter 8. Procedures for estimates the amount of water required for leaching are presented in Chapter 7. Leaching for control of soil salinity does not always need to be provided at each irrigation. Pre-plant irrigation may adequately leach the surface soil for new seedlings. Depending on the sensitivity of the crops to be grown and the rainfall during the winter season, planning for leaching during the low ET-demand rainy period may make more effective use of rainfall.

Estimating the design capacity in subhumid and humid areas can be more complicated than in arid areas. The economic benefit of irrigation in subhumid and humid areas is derived mainly during extended drought periods. If the irrigation system is not able to replenish water during these periods, the potential economic benefits of irrigation may not be achieved. These issues are discussed in detail in Chapter 8.

2.3.4 Drainage Requirements for Water and Salinity Control

In the 1990s, the World Bank (IBRD) estimated that a quarter of all irrigated land was affected by salinity caused by poor irrigation practices (IBRD, 1992b). On newly irrigated land, some 10 to 50 years may be required for excess water to fill the underlying unsaturated zone. If excess water input is ignored during this period, the rise in the water table inevitably results in waterlogging unless the natural drainage capacity increases with the rise in the water table. On a project basis, well-designed farm irrigation systems and efficient management of excess water from the start of a project can delay the need for increased drainage capacity for many decades, or in some cases prevent the need to install additional drainage facilities (Jensen, 1993).

The benefits of controlled drainage are beginning to receive more attention. This means that drainage is allowed only when the water table needs to be lowered to prevent crop damage or when encouraging leaching of salts. Abbott (2003) reported a study that showed that controlled drainage can give significant benefits to both the farmer as increased yields and to the wider community in terms of reduced water requirements. Areas of potential application for controlled drainage were identified in North Africa (Algeria, Egypt); the Middle East (Israel, Syria, Iraq, Bahrain); India (Punjab, Haryana, Rajasthan); and Asia (Pakistan, Northern China, Central Asian States).

The need for increased drainage capacity is strongly linked to the types of farm irrigation systems used and how they are managed. When most new irrigation projects were dominated by surface irrigation, increased drainage capacity was nearly always an essential requirement for sustained agricultural productivity. With improved irrigation systems that apply water more uniformly and with more efficient water management practices including deficit irrigation, the capacity of large-scale drainage above the existing natural capacity may be decreased. However, because of nonuniform subsoils, some increased localized drainage capacity will usually be required in most new irrigation projects. Seepage from unlined canals and ditches can also cause high water table levels and increase drainage requirements. Details on salinity control and drainage requirements and design can be found in Chapters 7 and 9.

Reuse of waste effluents has become a common practice where renewable water supplies are limited. Use of irrigated agriculture to dispose of waste effluents has also become an accepted and preferred practice over adding this burden to sewage treatment plants. Special management practices may be required and there usually are limitations on the types of crops on which waste effluents can be used. Details on use of waste effluents in irrigation are presented in Chapter 20.

2.4 SYSTEM DESIGN AND INCREASING COMPETITION FOR RENEWABLE WATER SUPPLIES

Increasing competition among water uses will increase pressures on irrigated agriculture because agriculture consumes most of the renewable water supplies in most semiarid and arid areas. These pressures will become more severe as water supplies are more fully utilized. Conflicts will increase. Solutions to these conflicts may result in revisions of water laws and allocations. In the future, the price of water will be more closely related to its real economic cost or value. This will affect irrigated agriculture because the marketable product of many crops per unit volume of water consumed is low.

The designer working with individual farmers or on farm irrigation systems for a new project or a project that is being modernized must consider the available water supplies, particularly renewable water supplies. These supplies are not only based on hydrological aspects and the physical facilities available to store and deliver the water, but on legal and social aspects. In the U.S., an individual farmer's *water right* to water from a common surface water source is the most common assurance of a renewable water supply. In some cases, the water right may be granted to an quasi-public irrigation district rather than to individuals. It is generally understood that in the western U.S., when a water right is sold or transferred, only that portion of the right that is used consumptively can be transferred.

If groundwater is the only source of water, then the expected recharge rate relative to the expected annual withdrawal rate must be considered to determine if the water supply can be sustained indefinitely, or at least until the investment in the irrigation system can be recovered. In areas where groundwater is essentially being mined, as in parts of the Ogallala aquifer of the Great Plains, state water laws regulating pumping must be considered. In addition, if groundwater is being mined, the rates of withdrawal and declining well-yields as the saturated layer decreases must be factored into the planning and design process. Renewable water supply issues are not covered in depth in this monograph. Details addressing hydrologic issues and water storage and conveyance systems must be obtained from other sources.

The U.S. has agreements with Canada and Mexico on sharing common water supplies. However, in many regions, no international agreement governs sharing waters of rivers that flow through several countries. More than half the world's largest rivers flow through two or more countries. The potential for conflict over shared water is increasing greatly. The implications for food security and managing irrigation projects are enormous (Jensen, 1993). International law for sharing water will become more important as competition increases. Guidelines for international agreements are available (Kimball, 1992).

2.4.1 Environmental Aspects, New Dimensions

The International Conference on Water and the Environment, held in Dublin in January, 1992, focused on sustainable development, management, and utilization of water resources in harmony with environmental conservation. It identified environment and development priorities to be agreed upon at the June, 1992, United Nations conference in Rio de Janeiro. *Agenda 21*, adopted at the Rio conference, gave high priority to win-win policies of poverty reduction, economic efficiency, and economic development. Also about this time, the policy of the World Bank relative to new projects changed. The Bank staff now required investment projects to be classified based upon their potential environmental impact. Projects in Category A required a full environmental assessment. These include dams and reservoirs and large-scale irrigation projects (IBRD, 1992a). Policies for sustained development include "removing subsidies that encourage excessive use of fossil fuels, irrigation water, and pesticides and excessive logging" (IBRD, 1992b, p. 2).

The possible trade-offs between water for food production and water for nature became one of the most contentious issues in discussions of the Second World Water Forum in The Hague in 2000 (Rosegrant et al., 2002). They concluded that this conflict might be one of the most critical problems to be tackled in the early 21st century.

Gleick (2002) indicated that in the early 20th century in the U.S. West and throughout the world, water left in the stream was considered "wasted." The language of water development and reclamation indicated a perception that water was a resource to be extracted and put to use. The meaning of *beneficial use* of water is beginning to expand from a narrow economic interpretation to a broader view recognizing the growing public awareness of the value of environmental resources. South Africa has formally recognized the right to water for natural ecosystems in their new water laws and constitution (Gleick, 2002). In the U.S., competition for water for endangered species and wildlife, such as for the whooping crane in Nebraska and salmon in northwest rivers, will affect water supplies available for irrigated agriculture

The increasing demand for domestic and other water uses may affect the order of water reuse. Foe example, Falkenmark and Widstrand (1992) suggested that because domestic use requires the cleanest water, the ideal order of reuse would be household first, then industry, then agriculture. Agricultural use would be last because most irrigation water is consumed, i.e., it returns to the atmosphere through evapotranspiration and is not available for reuse. This concept is becoming very real in some areas as clean water is being provided first to municipalities. Agriculture, which used to have first access to the water, is being required to use municipal return flow.

2.4.2 Water Supply and Consumption

In semiarid areas, the area of irrigated land alone does not indicate the volume of irrigation water that is consumed because of variable rainfall and because some crops are often not fully irrigated. Likewise, the traditional concept of irrigation efficiency is not very meaningful when considering water supplies for irrigation and water consumed by evaporation and transpiration. A better procedure for accounting for water use, based on a water balance approach, was developed by Molden (1997). *Water accounting* is a procedure for analyzing the uses, depletion, and productivity of water in a water basin context. A key term is *water depletion*, which is the use or removal of water from a water basin such that it is permanently unavailable for further use as a liquid within the basin. He described process and non-process depletions. *Process depletion* is where water is depleted to produce an intended good. In agriculture, process depletion is transpiration plus that incorporated into plant tissues—the product. *Non-process depletion* includes evaporation from soil and water surfaces and any non-evaporated component that does not return to the freshwater resource. It would also include depletion by weeds and other non-economic vegetation. The *depleted fraction* is that part of inflow that is depleted by both process and non-process uses of water. The *productivity of water* is a performance parameter that can be related to the physical mass production or economic value per unit volume of water. Molden suggested that the productivity of water can be measured against gross or net inflow, depleted water, process-depleted water, or available water in contrast to the production per unit of water consumed in ET (Viets, 1962).

Water accounting can be done at various levels such as the field, irrigation service, basin, or sub-basin levels. Molden et al. (1998) presented a detailed example of water accounting at the basin level using data from Egypt's Nile River, where some detailed information on water use and productivity was available. Molden and Sakthivadival (1999) presented another example for a district in Sri Lanka.

Numerous conferences have been held resulting in papers concerning the quantification of *real water*, which is water that may be available for transfer or reallocation to higher value uses. Irrigation efficiency concepts enter in when discussing possible real water amounts that can be saved and made available for transfer by making changes on irrigated lands. Roos (2001), in discussing agricultural water conservation in relation to water available for transfer to another basin, stated: "Unless evapotranspiration can be reduced, such measures do not add to the regional supply. Depletion remains essentially the same even with greater application efficiency...." His comments related to the Sacramento and San Joaquin valleys, which function like closed basins. He also stated: “But the general rule is still valid: unless depletion changes, there is no real water savings available for transfer.”

2.5 IRRIGATION WATER MANAGEMENT DURING DROUGHTS

Changes in water rights of renewable water supplies from agriculture to higher value uses have been underway in the western U.S. for decades. Today, new methods and practices are used to provide temporary exchanges in water supplies. For example, when water supplies are plentiful, farmers who irrigate continue to use the water available under their water rights, but when annual supplies are below normal, temporary exchanges in water uses have become more common.

NRC (1992) summarized some of the mechanisms being used to provide flexibility in the use of renewable water supplies. The NRC Committee discussed various water market mechanisms, third party impacts, water transfer opportunities, and the role of water law in the transfer process. Case studies of water transfers in several areas of the West were presented along with several examples of water banking practices.

2.6 OTHER AGRICULTURAL PURPOSES AND BENEFITS OF IRRIGATION

Irrigation is used mainly to provide water used in ET and for control of soil salinity. However, irrigation is also used for other purposes that are associated with irrigated agriculture. These secondary uses may be important to the success of an irrigated enterprise. Some of the special uses that need to be considered by the designer are summarized below. The designer should consider local practices and special crop needs when planning and designing an irrigation system.

2.6.1 Soil Conditioning

In arid areas, where crops are planted to meet specific marketing opportunities, irrigation is essential to germinate and establish plants because rainfall may not occur at planting time or is not dependable. In some areas, solid set sprinklers are set up solely for this purpose and then removed after the new crop has been established. After establishing the new crop, irrigations are continued using the existing irrigation system, which is usually a surface system.

2.6.2 Crop Cooling

Crop cooling is one of several special uses of irrigation. It is a minor component of irrigated agriculture, but is used on diverse crops for various purposes. For example, when planting lettuce in the Imperial Valley of California about mid-September, daily 3-hour sprinkler irrigations are applied to cool the germinating lettuce seedlings until they are established. Vineyards have been irrigated for 2 to 3 minutes at 15-minute intervals to cool the plants down to 8° to 14°C. Other crops that have been cooled by sprinkler irrigation are almonds, apples, beans, cherries, cotton, cranberries, cucumbers, flowers, potatoes, prunes, strawberries, sugar beets, tomatoes, and walnuts (Sneed, 1972; Gray, 1970; Kidder, 1970; Carolus, 1971; Unrath 1972a,b). Air conditioning of crops for higher yield and better quality has been studied in California, Michigan, and Washington. Summaries of crop cooling principles have been presented by Chessnes et al. (1979) and Merva and Vandenbrick (1979). Evaporative cooling of apples in North Carolina has increased their red color and soluble solids (Unrath and

Sneed, 1974). Sprinkler irrigation has been used to delay fruit bud development in Utah to avoid damage due to low spring temperatures (Alfaro et al., 1974; Anderson, 1974). Irrigation designers should consider recent technological developments, local practices, and current economics in planning crop cooling by irrigation.

2.6.3 Frost and Freeze Protection

Freeze protection is another special use of irrigation. By coating plants with water as air temperatures drop below freezing, the heat of fusion released as the water freezes maintains the plant temperature at 0°C. The ice coating on plants must continually be in contact with unfrozen water until the ice melts. Early studies have shown that plants could be protected against freezing against temperature as low as –9°C with no wind and applications of 6.5 mm/h. Early studies of frost and freeze protection for small fruit, flowers, potatoes, and grapes were described in the first edition (Braud and Horthorne, 1965; Harrison and Gerber, 1965; Loscascio et al., 1967; Lamade, 1968; Kidder, 1970; Sneed, 1970; Braud and Esphahani, 1971; Harrison et al., 1974). Severe freezes in Florida in the 1980s killed about 82,000 ha of citrus. Since then, microsprinklers have largely replaced heaters and wind machines in Florida (Parsons and Wheaton, 1995).

Various techniques for frost and freeze protection were discussed in an ASAE monograph, *Modification of the Aerial Environment of Crops,* by Barfield and Gerber (1974). The designer should consider recent technological development, local practices, and current economics in planning for frost and freeze protection by irrigation.

2.6.4 Soil Conditioning

In arid areas, the surface soil may become very dry following the harvest of the previous crop. In these areas, it is often impossible to prepare a seed bed for small-seed crops without first moistening the surface soil. Thus, irrigation becomes a necessity for mechanical purposes rather than providing water for plant growth. Similarly, irrigation may be necessary to permit harvesting root and tuber crops such as sugar beets, potatoes, and peanuts. Much of the water applied for this purpose may be stored as soil water for use by the next crop, stored for the next cropping season, or used to leach salts.

2.6.5 Applications of Chemicals in Irrigation Water

Application of fertilizers, pesticides, herbicides, desiccants, and defoliants—chemigation—is well established and documented. Because this practice has become so widespread a new chapter has been added on this subject (see Chapter 19).

2.7 SYSTEM DESIGN AND OPERATION CHALLENGES

Recent and emerging design issues concern environmental aspects affected when using surface runoff from surface irrigation systems. These include any pesticides and plant nutrients that may be included in the runoff, erosion and sediment deposition in the collecting flow channels and receiving water bodies. Likewise, when converting from surface irrigation systems to drip or sprinkler systems, wetlands that had developed from previous irrigation practices may gradually dry up. The impact of both surface and subsurface water quality on instream and downstream water uses will become significant factors in the future if not already a factor in the area under consideration. Designers of irrigation must also consider the various legal, environmental and physical constraints that may affect the design and operation of an irrigation system.

Today, designers of irrigation systems must take into account many other aspects in addition to those considered essential several decades ago. Economic aspects will be more challenging if stable renewal water supplies are not assured and prices received for farm produce fluctuate widely. English et al. (2002) indicate that irrigated agriculture will need to adopt a management paradigm that is based on maximizing net benefits rather than maximizing yields. Irrigation to maximize benefits will be more complex and challenging than the conventional practice of maximizing crop yields per unit of land. Two important concerns are sustainability and risk. The increased complexity of analysis will require more sophisticated analytical tools.

One of the basic concepts of surface irrigation in the past is that there must be surface runoff if the lower ends of the borders or furrows are to be irrigated so as to replace most of the available water. In many areas, because of declining water tables and limited water supplies, surface runoff is being restricted or prohibited. The general approach in coping with this restriction was to install recirculating or pump back systems or to physically prevent surface runoff. Recirculating systems are required in some areas. The challenge to designers who are restructuring surface systems is to consider variable grade systems that can increase the head to tail end uniformity of water application with little or no surface runoff. The concept is not new (Powell et al., 1972). However, such a design can be very complex when considering varying infiltration rates with or without furrows, the variation in vegetative growth in border strips and some row crops during the year, and the special requirements of some crops. Again, there will be need for more sophisticated analytical tools to address these complex relationships. Chapters 13 and 14 address these issues and provide the concepts and tools necessary for meeting these design challenges. Chapters 15-17 address the design of sprinkler and microirrigation systems.

In developing countries, the stability of a community organization is essential for sustained and productive irrigated agriculture. Rapidly increasing populations and relatively stable renewable water supplies often involve complex social, food security, and natural resources issues. Addressing these issues will be a major challenge to designers of new or improved irrigation systems to consider, especially in developing countries.

2.8 SUMMARY

The factors to be considered in the design and operation of farm irrigation systems have changed greatly since the first edition of this book was published in 1980. In this chapter, I have attempted to highlight key factors that will influence the design and operation of new irrigation systems and the upgrading of old systems in order to make irrigated agriculture more productive and more sustainable. Some of these factors are renewable water supplies, coping with droughts, adequacy of drainage, control of salinity, the productivity of water and water use efficiency, new management concepts such as deficit irrigation, and environmental concerns about surface runoff. I have cited references where readers can find additional details on the problems and issues that will need to be addressed by irrigation system designers, trainers providing irrigation management guidance, and operators of irrigation systems. Sustainable and productive irrigated agriculture will require adopting new technology and management concepts and increased emphasis on the productivity of irrigation water.

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