Part I Fundamentals

1 Introduction

1.1 PRELIMINARY REMARKS

Irrigation is vital for productive agriculture and consequent food and nutritional security. Agriculture is either rainfed or is dependent on irrigation. In either case, it is greatly impacted by the vagaries of nature, especially weather, as well as by soil, crops to be irrigated, and the source, availability, and quality of water. Irrigation is needed for productive agriculture and consequent food and nutritional security, because rainfall is seldom adequate and timely for meeting agricultural needs, even in humid areas. Also, non-agricultural lands, such as wastelands, can be brought under agriculture by irrigation, and less productive land can be transformed into more productive land. Rainfall varies from place to place for a given month or year and from month (or year) to month (or year) for a given place, as illustrated in Figures 1.1–1.3 for the United States. Figure 1.1 depicts the monthly distribution of rainfall at different places, Figure 1.2 shows the annual precipitation from 1982 to 2010 at different places, and Figure 1.3 shows the percentage of normal precipitation in January 2015.

The requirement for irrigation is significantly affected by climate. In the United States, there are four main types of climate regions: arid, semi-arid, sub-humid, and humid, as shown in Figure 1.4. These climate regions are delineated by the Köppen–Geiger climate classification system based upon the annual and monthly averages of temperature and precipitation (Beck et al., 2018). In arid and semi-arid areas, irrigation is needed for growing crops. In humid and sub-humid areas, there may be enough annual rainfall, but it is not timely distributed when needed and hence irrigation may be required. Even in humid areas, periods between rainfall events may be too long and crops may suffer due to the lack of moisture. Crops in certain soil conditions begin to suffer if they do not receive water within five days or less. Droughts also occur, and their frequency seems to be increasing due to climate change and global warming, thus necessitating irrigation.

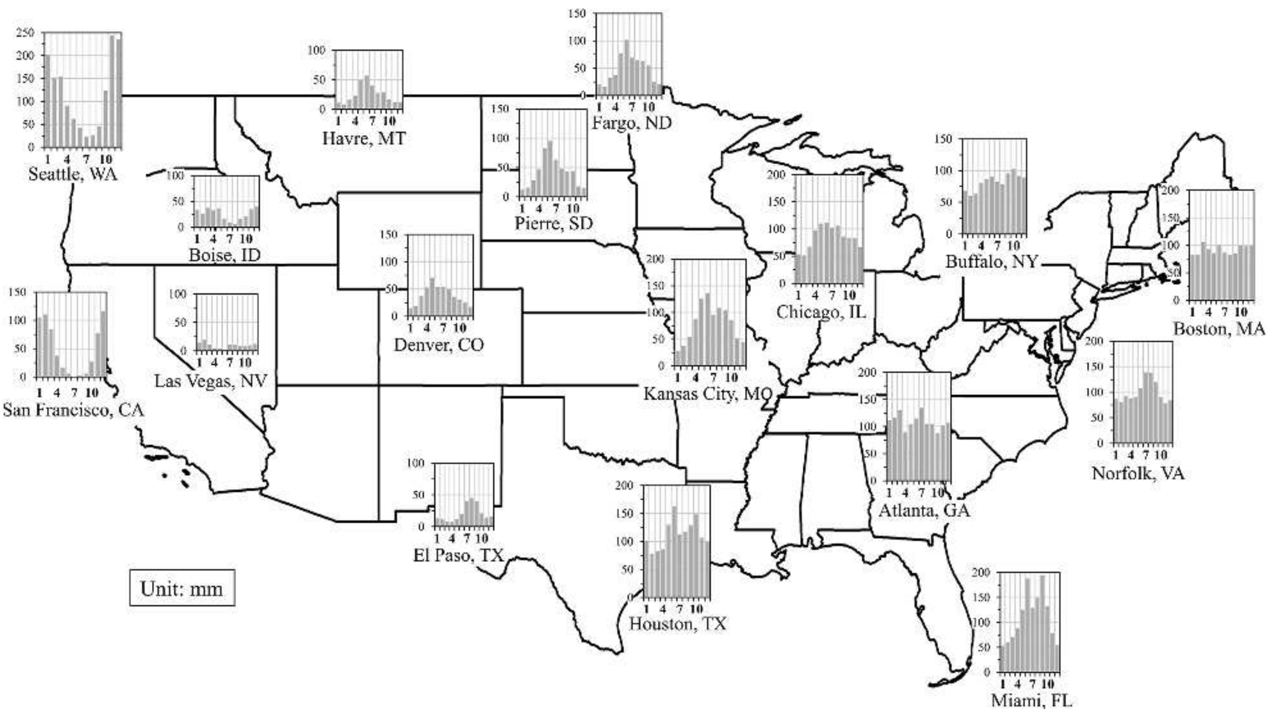

Figure 1.1 Average monthly precipitation distribution across the United States. (Data from NOAA Regional Climate Centers during 1980–2015, http://scacis.rcc-acis.org.)

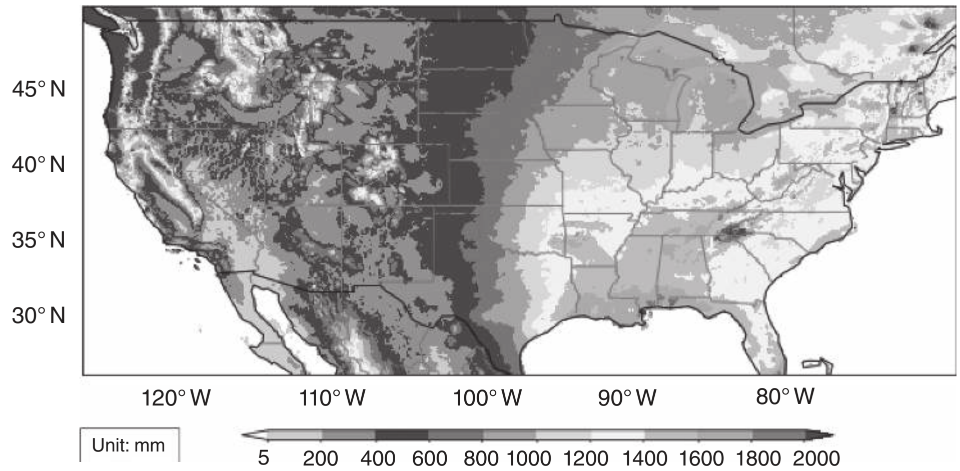

Figure 1.2 Average annual precipitation in millimeters during 1982–2010 across the contiguous United States. (Data from Daily Surface Weather and Climatological Summaries, DAYMET, https://daymet.ornl.gov.) A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.

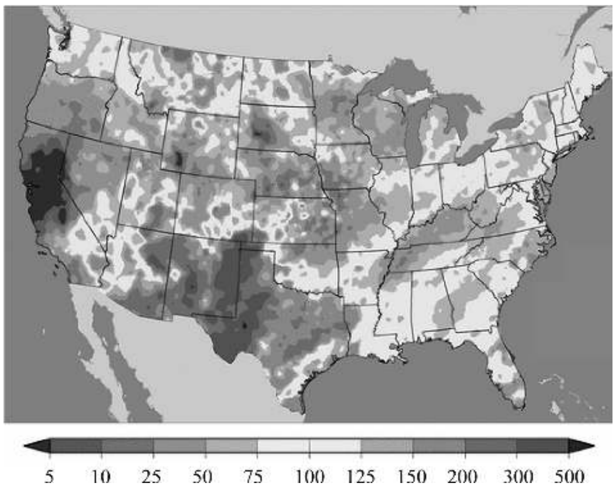

Figure 1.3 Percentage of the normal precipitation in January 2015 across the United States. (Data from NOAA National Climate Report, www.ncdc.noaa.gov/sotc/national/201501.) A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.

Irrigation of agricultural lands is now practiced all over the world. The purpose of irrigation is to provide water to crops where and when crop water requirements cannot be met by natural rainfall. In many areas, there is deficit rainfall and in some areas rainfall is not enough during the crop-growing season, and in other areas there is hardly any rainfall. Many areas without or with little rainfall are wastelands, but they can be transformed by irrigation into crop-producing areas.

Providing a snapshot of irrigation worldwide as well as in the United States, this chapter discusses different aspects of irrigation, including need, importance, and development. It also discusses the organization of the book, irrigation practices, and environmental concerns arising due to irrigation, and concludes with a reflection on the future of irrigation.

1.2 ORGANIZATION OF CONTENTS

Before discussing the scope of the book, it is desirable to point out the interaction or overlap of irrigation engineering with other disciplines, as shown in Figure 1.5, such as climate science, water resources (including water quality), soil science, crop science, hydraulics, hydrology, environmental impact assessment, economics, and management. These disciplines define the factors that influence the planning, design, and management of irrigation systems and in turn define the domain of irrigation engineering. The techniques developed in these disciplines are brought to bear on solutions to irrigation problems.

Irrigation engineering borrows techniques from solutions in non-engineering disciplines, such as mathematics, statistics, operations research, probability theory, social sciences, economics, and law. For farming, irrigation is almost always required and irrigation systems are therefore planned, designed, built, operated, and managed. There are a number of considerations that need to be kept in mind for planning, designing, operating, and maintaining an irrigation system, as shown in Figure 1.6. The first consideration is the selection of crops. However, before selecting crops for cultivation on an area of land, it is important to know five things: climate, soil, source and availability of water and energy, quality of water, and crop types. The crops selected for cultivation depend not only on these things, but also on irrigation.

The second consideration includes principles of hydraulics, which are needed for bringing water from its source to the field. Water is transported either by open channels or pipelines, and often it may need to be lifted using pumps. Also, for proper application of water, it is important to measure its flow. The third consideration comprises hydrologic principles that are needed for the application of water. Once water is applied to the land, it has four ways to go: vertically downward (infiltration and percolation), temporary storage in the pore spaces of soil (soil water), horizontal movement

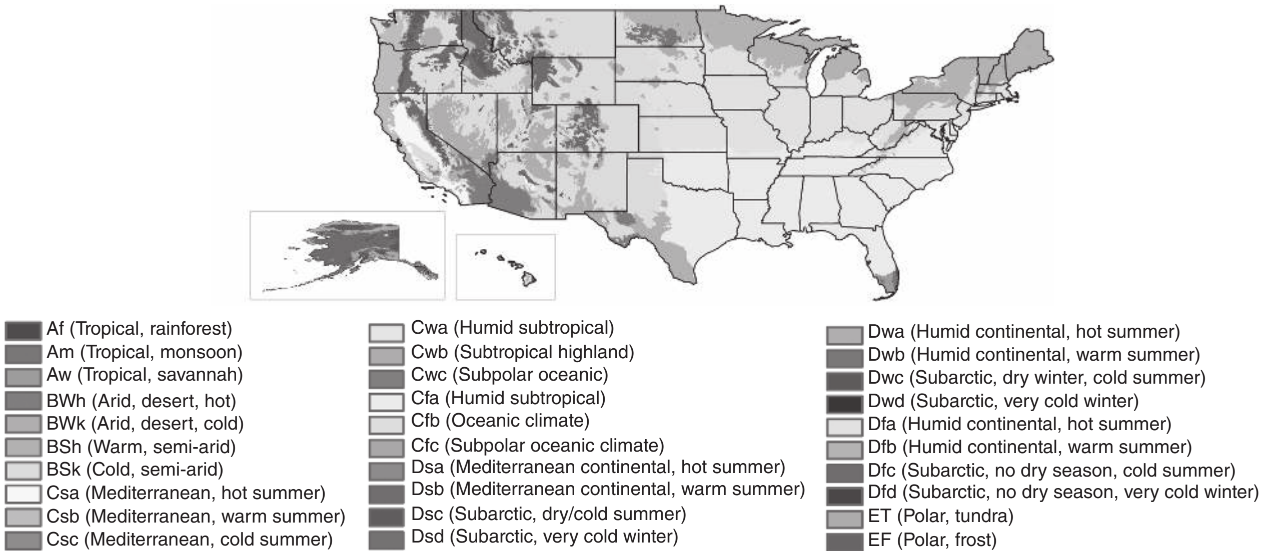

Figure 1.4 Köppen climate classification for the United States. (Data from Beck et al. [2018] using weather data from 1980–2016.) A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.

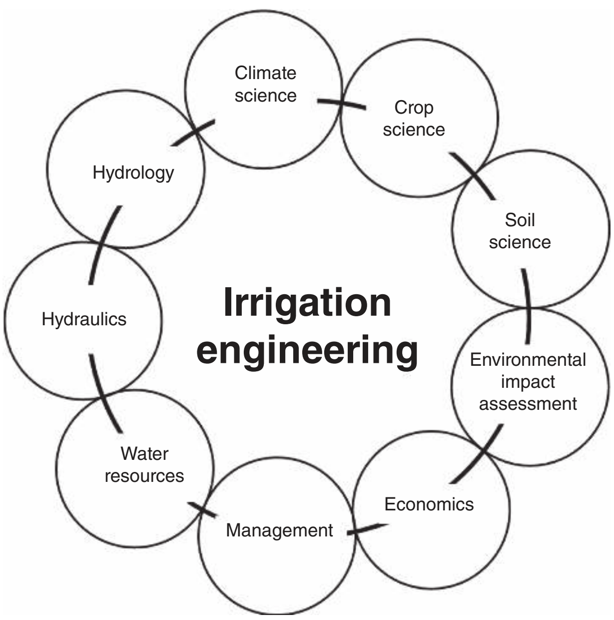

Figure 1.5 Irrigation engineering interfacing with other disciplines.

(drainage and seepage), and vertically upward (evapotranspiration), combining evaporation and transpiration.

The fourth consideration comprises irrigation principles, which include consumptive use, irrigation efficiency, and equations governing flow over porous beds. In general, crops do not consume water at the same rate or in the same amount, so crop water consumptive use becomes important. The fifth consideration includes methods of irrigation, including basin, border, furrow, sprinkler, and trickle (or drip). The sixth consideration entails design, operation, and management of irrigation systems, including land leveling, drainage, irrigation scheduling, environmental considerations, economic evaluation, and maintenance.

1.3 DEFINITION OF IRRIGATION

Irrigation is defined as artificial application of water to plants for overcoming the lack, insufficiency, or poor distribution of rainfall. It is the controlled application of water to croplands, with the primary objective of creating an optimal soil moisture regime for maximizing crop production and quality, and at the same time minimizing environmental degradation inherent in the irrigation of agricultural lands. Irrigation is critical for food as well as nutritional security, especially in semi-arid and arid areas, and will become even more so with increasing population and under the specter of climate change.

1.4 BENEFITS OF IRRIGATION

Irrigation has several benefits, including the following: (1) It increases the productivity of agricultural lands, as shown in Table 1.1 for Brazil and in Table 1.2 for different states in the United States (Figure 1.7 shows the percentage increase in different crop yields in the United States [US Department of Agriculture, 2002]); (2) it makes it possible to have more than one harvest per year; (3) it guarantees production by removing water deficit; (4) it enables harvesting of crops in the off-season; (5) it permits growing more crops in a year on the same land; (6) it leads to improved product quality; (7) it allows growing crops that are highly sensitive to moisture deficit but are economically more profitable; (8) it permits transformation of agriculturally unproductive areas into agriculturally productive areas; (9) it creates jobs; and

(10) it helps arrest migration of people from rural areas to urban centers.

1.5 LIMITATIONS OF IRRIGATION

Irrigation is not without limitations, some of which are as follows. Traditional methods of irrigation – such as flooding, border, and furrow – require large volumes of water, hence irrigation management is needed. Modern methods of irrigation have high implementation costs. They may need hand-specialized labor which may not be available or may be too expensive. If not properly done, irrigation may lead to salinization of soils, so soils need to be appropriately managed. Irrigation has environmental impacts, such as water logging, waste of water, generation of mosquitoes, and changes in ecosystems, that need to be minimized.

Table 1.1 *Increase in yield due to irrigation in Brazil*

Crop	Not-irrigated (kg/ha)	Irrigated (kg/ha)	Increase in yield (%)
Cotton	848	2,700	218
Rice	1,739	3,750	115
Beans	388	2,300	492
Corn	1,985	5,500	177
Soyabean	1,844	3,000	62
Oat	1,668	3,400	104

1.6 NEED FOR IRRIGATION

The demand for food is increasing each year because of the growing population, rising food requirements, and increasing standards of living. Further, a lot of food grains and other agricultural produce are wasted during harvesting, transportation, distribution, storage, and consumption, as shown in Figure 1.8. The per capita food loss in Europe and North America is 280–300 kg/year. In sub-Saharan Africa and South/Southeast Asia it is 120–170 kg/year (FAO, 2011). This means that more food will have to be produced to ensure food security. In the next 35–45 years, world food production will have to be doubled in order to meet the demands of increasing population. It may be noted that 90% of this increased food production will have to come from existing lands, and 70% of this increased food production will have to come from irrigated lands.

Nearly 20% of the cultivated area in the world uses irrigation, and this area generates 44% of the agricultural production of the world. For example, 5% of the total area in Brazil uses irrigation, and this area produces 18% of agricultural produce in the country. Irrigated and rainfed agricultural lands and their production in different countries are shown in Figure 1.9.

The increase in irrigated land has not kept pace with the increase in global population, as shown in Figure 1.10. The decreasing trend of irrigation withdrawal since the 1980s with a growing population in the United States, as shown in Figure 1.11, poses a challenge to design even more efficient irrigation techniques and systems.

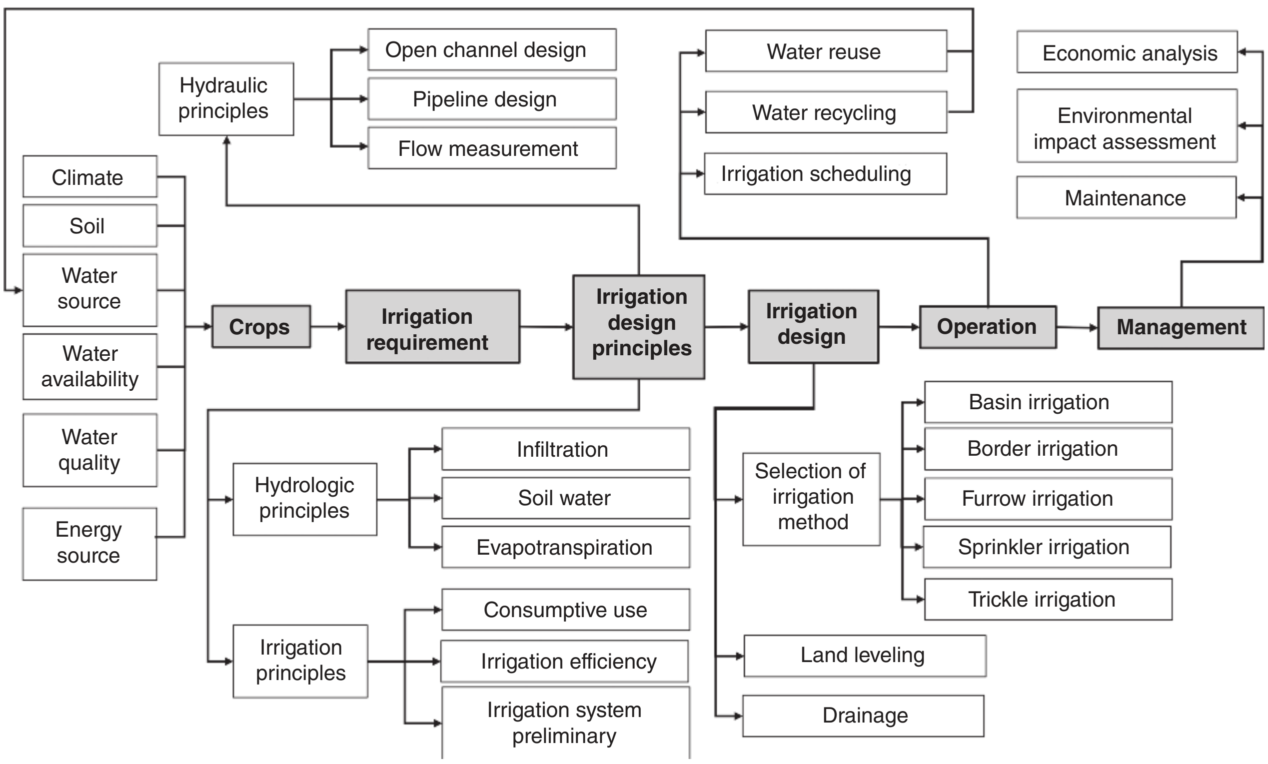

Figure 1.6 Planning, designing, operating, and managing an irrigation system.

Table 1.2 *Average yields of non-irrigated crops in comparison with irrigated crops*

	Yield per acre				Yield per acre		
Crops, state, and year	Non-irrigated	Irrigated	Increase	Crops, state, and year	Non-irrigated	Irrigated	Increase
Alfalfa				**Pole beans**			
North Dakota (1966)	2.0 tons	4.4 tons	2.4 tons	Georgia (1950)	2,583 lb	6,025 lb	3,442 lb
South Dakota (1966)	2.5 tons	5.3 tons	2.8 tons	**Potatoes (Irish)**			
Cabbage				Arizona (1964–5)	NGWI	6.5 tons	6.5 tons
New Jersey (1955–9)	12.5 tons	18.9 tons	6.4 tons	California (1968)	350 sacks	450 sacks	100 sacks
Corn				New York (1946)	NP	NP	57 bu.
Florida (1971)	115 bu.	190 bu.	75 bu.	Texas	1.5 tons	7.0 tons	5.5 tons
Nebraska (1966)	36 bu.	102 bu.	66 bu.	Wisconsin (1946)	NP	NP	100 bu.
North Carolina (1963–8)	101 bu.	139 bu.	38 bu.	**Silage**			
North Dakota (1966)	44.0 bu.	77.9 bu.	33.9 bu.	Alabama (1966–8)	31 tons	47 tons	16 tons
South Dakota (1949–55)	32.0 bu.	92.0 bu.	60 bu.	**Soybeans**			
Virginia (1954–5)	83.3 bu.	109.2 bu.	28.9 bu.	Arkansas (1966–8)	28.9 bu.	37.2 bu.	8.3 bu.
Cotton (lint and seed)				Georgia (1978)	30 bu.	53 bu.	23 bu.
Arizona (1964–5)	NGWI	2,137 lb	2,137 lb	Missouri (1959)	NP	NP	8.0 bu.
Arkansas (1950–2)	1,608 lb	2,083 lb	475 lb	**Sugar Beets**			
Georgia (1949–53)	1,216 lb	1,902 lb	686 lb	Arizona (1964–85)	NGWI	20.5 tons	20.5 tons
Missouri (1953)	1,414 lb	2,683 lb	1,269 lb	North Dakota (1949–52)	NGWI	20 tons	20 tons
North Carolina (1963–7)	1,836 lb	1,932 lb	96 lb	Wyoming (1956)	NGWI	16 tons	16 tons
South Carolina (1954–5)	1,077 lb	1,668 lb	591 lb	**Sweet Corn**			
Field beans (edible)				New Jersey (1955–8)	5,600 lb	11,900 lb	6,300 lb
Nebraska (1956)	27 bu.	54 bu.	27 bu.	**Sweet Potatoes**			
Grain Sorghum				Louisiana (1953–6)	117.9 bu.	271.9 bu.	154 bu.
Arizona (1964–5)	NGWI	72 bu.	72 bu.	**Tobacco**			
Nebraska (1966)	39 bu.	87 bu.	48 bu.	South Carolina (1951–4)	1,183 lb	1,547 lb	364 lb
Oklahoma (1958–62)	9.3 bu.	44.4 bu.	35.1 bu.	Virginia (1954–7)	2,699 lb	3,042 lb	343 lb
Grapefruit				**Tomatoes**			
Florida (1960–7)	735 bo.	1,056 bo.	321 bo.	Georgia (1947–53)	17,430 lb	23,485 lb	6,055 lb
Oranges				**Wheat**			
Florida (19600–67)	369 bo.	493 bo.	124 bo.	Kansas (1954–9)	21 bu.	48.6 bu.	27.6 bu.
Peanuts				Oklahoma (1954)	13 bu.	34 bu.	21.0 bu.
North Carolina (1963–68)	2,632 lb	3,168 lb	536 lb	Texas (1966–7)	15.8 bu.	53.8 bu.	38 bu.
Oklahoma (1956–59)	1,014 lb	2,306 lb	1,292 lb				
Peaches							
Maryland (1955–64)	300 lb	372 lb	72 lb				

NGWI, not grown without irrigation; NP, not published; bu., bushels; bo., boxes.
Data from the US Department of Agriculture (www.ers.usda.gov/data-products/irrigated-agriculture-in-the-united-states)

1.7 PLANNING FOR AN IRRIGATION SYSTEM

Planning for an irrigation system entails answering a number of questions: (1) Should irrigation be done? (2) How much yield will irrigation increase? (3) How much will irrigation cost, and will it be affordable? (4) Is there sufficient water of good quality available? (5) What are the energy requirements, and can they be met? (6) What is the labor cost, and will labor be available? (7) How will the system be paid for? (8) What type of irrigation will be needed? (9) Will the irrigation system pay for itself in the long run? (10) Who will design the system? These and related questions need to be answered when planning for an irrigation system.

1.8 FOOD SECURITY

1.8.1 Population and Growth Pattern

The world population exceeded 6 billion in 2000 and it is projected to reach 9.7 billion by 2050 and 10.9 billion by the turn of 2100 (United Nations Population Division, 2019).

Cambridge University Press & Assessment
978-1-316-51122-0 — Irrigation Engineering
Vijay P. Singh , Qiong Su
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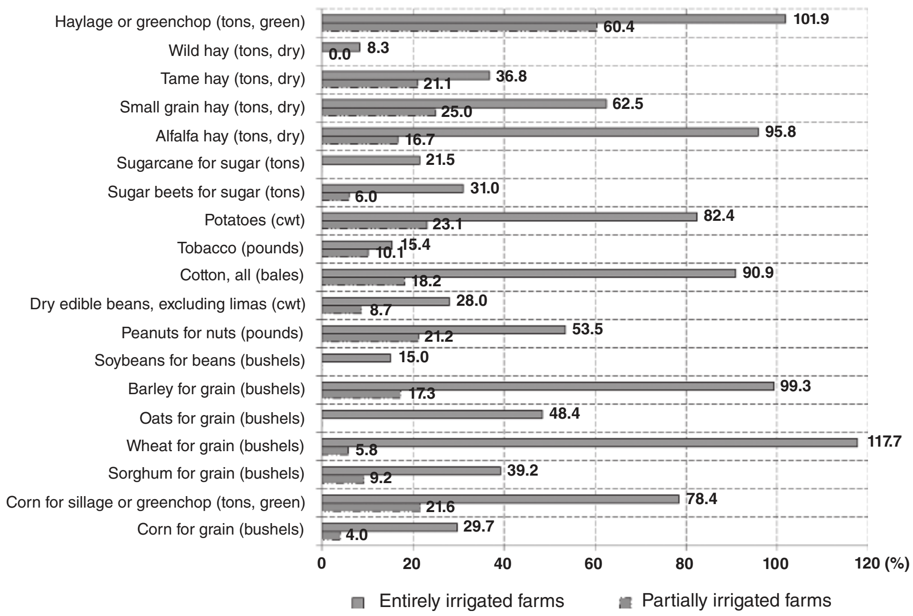

Figure 1.7 Percentage increase in average yield per acre of harvested crops in the United States (tons, cwt, pounds, bales, and bushels indicate different units used for crops yield in the United States). (Data from US Census of Agriculture, US Department of Agriculture, 2002.)

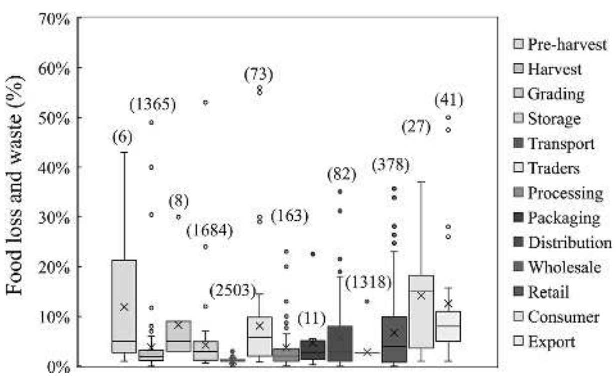

Figure 1.8 Range of reported global food loss and waste percentage during different processes (2001–2017). Number of observations is shown in brackets. (Data from FAO, 2019.) A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.

Interestingly, for most of human history the rate of increase of global population was relatively small until a century ago. However, the twentieth century witnessed a relatively rapid rise, resulting in the doubling of population, and population continues to grow at an alarming rate, as shown in Figure 1.12. The rapid growth is occurring in regions that are water stressed or are subject to droughts and extreme seasonal changes in precipitation and evaporation (Falkenmark and Widstrand, 1992). The pressure of the population in the top water-scarce areas in the world is shown in Table 1.3.

1.8.2 Food Requirement

The food requirements of a person depend on age, lifestyle, and work or level of activity. There is a large variation in the amount of food consumed daily from one country to another, and within the same country. In terms of calories, the US Department of Agriculture estimates that most women need 1600–2400 calories, while the majority of men need 2000–3000 calories each day to maintain a healthy weight. In the United States, the daily per capita consumption of food is 2730 grams, whereas on a global basis nearly 1880 grams of food is consumed per person on daily basis. Table 1.4 shows the temporal variation of per capita food consumption of different countries. This food comprises grains, dairy products, fruits, vegetables, meat, etc.

Food consumption has changed significantly over the past 100 years, as shown in Figure 1.13. These days, people eat more and waste more. To produce enough food to satisfy global food requirements, a huge amount of water is needed. For example, producing one ton of grains requires nearly 1000 m^3 of water. Much more water is needed to produce livestock products: for example, about 15,415 m^3 of water is needed to produce 1 ton of beef, as shown in Figure 1.14. There is a large variation in the water footprint of various foods and beverages, as illustrated in Figure 1.14.

Nearly one billion people, approximately one in six people globally, do not have access to adequate food at present. In India alone, nearly 195 million people are malnourished – about 25% of the global malnourished population. China has about 134 million malnourished people. Malnourishment is caused by poverty, inadequate supply chains, rampant food wastage, and poor farming. Ensuring food security requires good agricultural and management practices, advances in irrigation and technology, proper policies, and strong political will (Brabeck-Letmathe and Biswas, 2015).

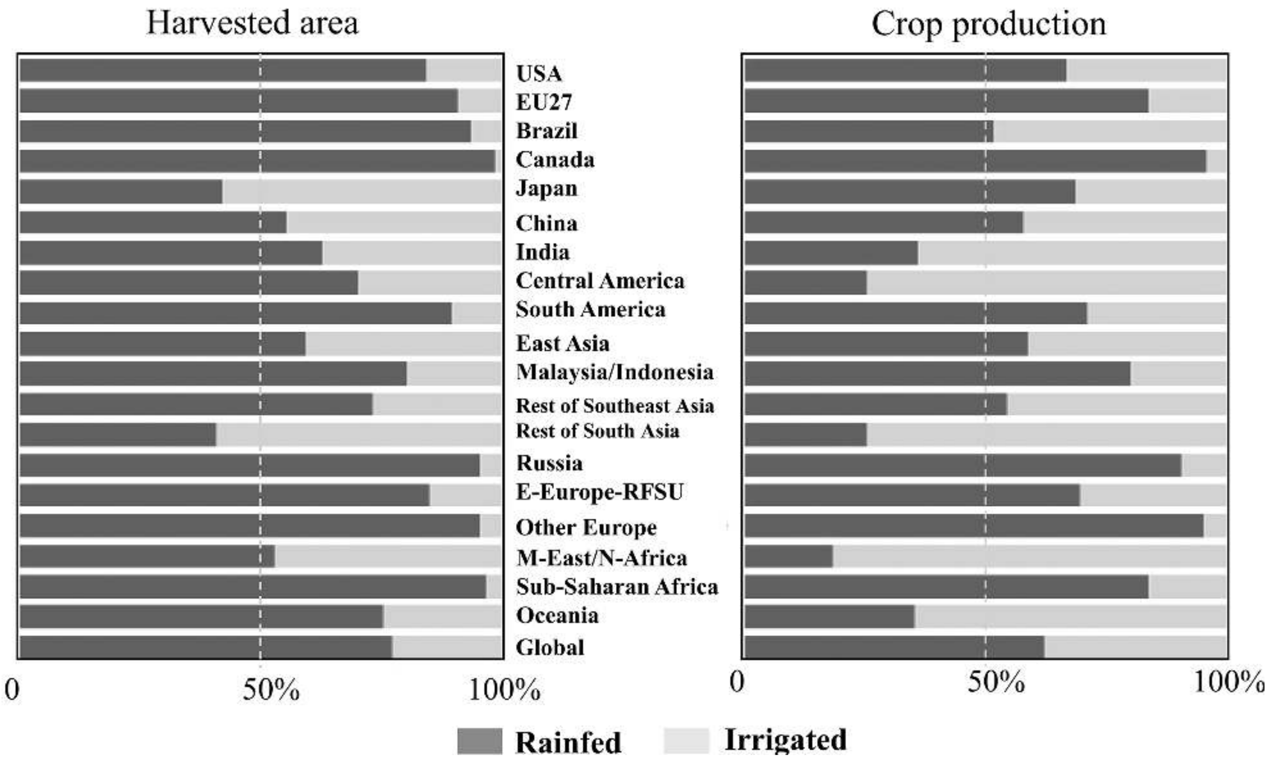

Figure 1.9 Percentage of irrigated and rainfed agricultural lands and their production in different countries (E-Europe-RFSU indicates Eastern European countries and a portion of former Soviet Union; M-East/N-Africa indicates the Middle East and North Africa). (Adapted from Taheripour et al., 2013.)

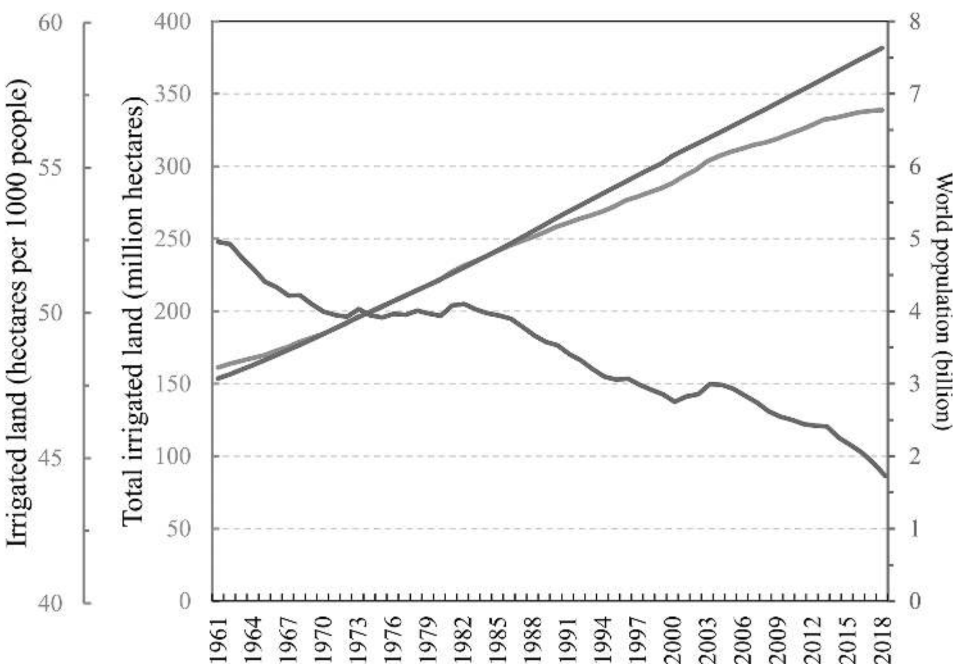

Figure 1.10 World population, world irrigated area, and hectares per 1000 people. (Data from FAO, 2020.) A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.

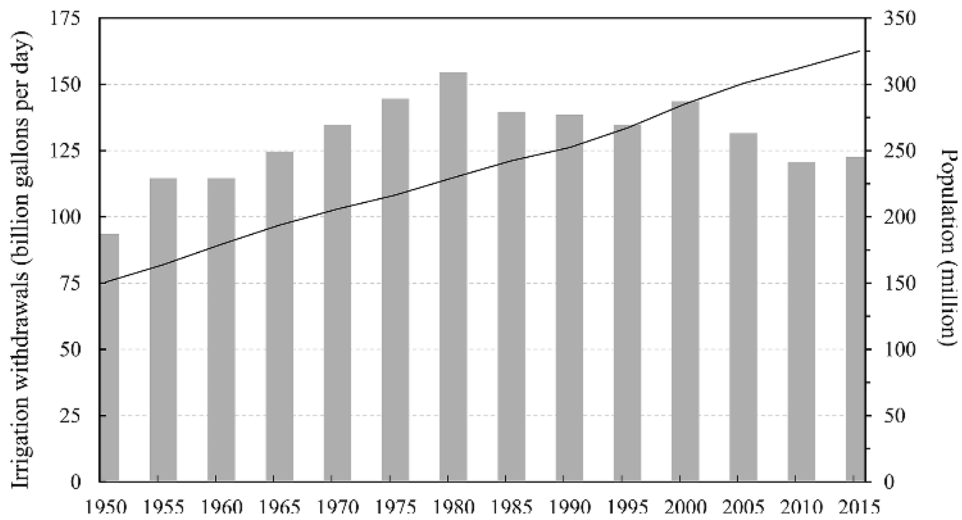

Figure 1.11 Trend of irrigation withdrawals with increasing population in the United States. (Data from US Geological Survey, http://water.usgs.gov/edu/wuir.html.)

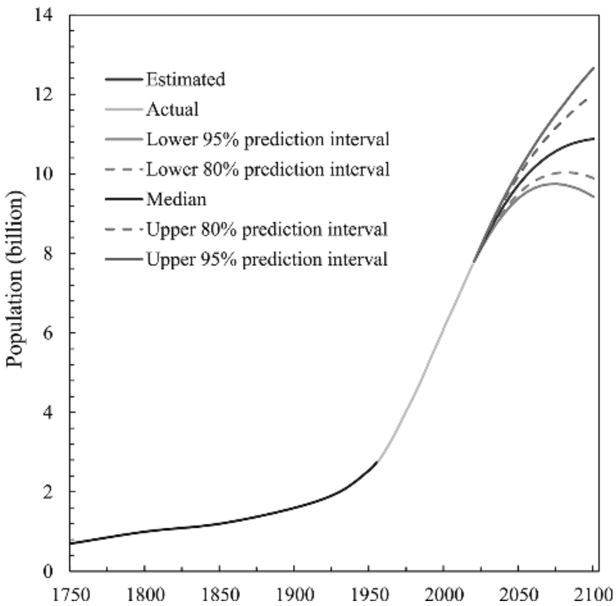

Figure 1.12 Population growth as a function of time. World population estimates from 1750 to 2100, based on the probabilistic median, and the upper and lower 80% and 95% prediction intervals of population projections. (Data from United Nations, DESA, Population Division, World Population Prospects 2019, http://population.un.org/wpp.) A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.

1.8.3 Rising Living Standards

The usual connotation of living standards has to do with the quality of life, which is measured by a number of factors, such as income, housing, healthcare, education, environmental quality, infrastructure, freedom, and social and cultural environment. There has been a substantial rise in the standard of living for the past 50 years all over the world, and this has translated into greater food and fiber requirements. Associated with this rise in the standard of living in rapidly developing economies is a steady increase in the demand for meat products and meat consumption (as shown in Table 1.5). For example, in China meat consumption rose from 20 kg/capita in 1995 to 99 kg/capita in 2017, increasing pressure on livestock production and water withdrawals. Consumption by an American is, on average, nearly the same as the consumption by nine Nepalis (Table 1.5).

1.8.4 Nutritional Security

Lack of food security is not the main or even the sole cause of malnutrition or lack of nutritional security. Many developing countries produce enough food to combat hunger, but a significant proportion of their population suffers from a lack of nutritional security, which encompasses malnutrition and obesity. This may partly be due to the lack of understanding of nutritional security, male domination resulting in gender discrimination, social taboos, lack of proper health education, corruption, and national pride. Nearly 3.1 million children under the age of five die each year because of malnutrition, accounting for about 45% of child mortality. About two-thirds of the world's malnourished people live in Asia and about one in four people living in sub-Saharan Africa is malnourished. The prevalence of undernourishment is the highest in Africa (as shown in Figure 1.15).

1.9 DEVELOPMENT OF IRRIGATION WORLDWIDE

Irrigation was introduced thousands of years ago in ancient civilizations. For example, irrigation started nearly 6000 years ago in Mesopotamia, 5000 years ago in the Nile River valley in Egypt, 4000 years ago in the Yellow