1 Introduction

Irrigation engineering is the analysis and design of systems that optimally supply the right amount of water to the soil at the right time to meet the needs of the plant system. The enterprise may be growing plants for food, landscape irrigation, or other purposes. Subsurface drainage engineering is the analysis and design of systems that remove water or salts from the soil in order to maintain as close to an optimal plant growth environment as possible.

System design and selection involves three steps. The first step is to characterize crop water requirements, hydrology, and soil characteristics. The second step is the hydraulic design of potential alternatives. The third step is an economic and environmental analysis. To adequately evaluate alternatives, it is important to look at all relevant inputs to the system (water, energy, labor) and at the effect of the system on the environment. Two consistent themes in this book are engineering economic analysis and assessment of environmental impact. Engineering economic analysis sums capital and annual costs in order to calculate the total present value cost of the system. Environmental assessment includes the estimation of such effects as chemical leaching, chemical runoff, soil erosion, and water resource depletion.

Design of irrigation and subsurface drainage systems involves the application of engineering, biology, and soil science in both synthesis and analysis methods of problem solving to assemble components that will fit together for a specific location and crop production system. Thus, aside from the knowledge of hydraulics and other engineering concepts, irrigation and drainage engineering require an understanding of the soil and water environment, soil-water-plant relationships, and hydrology. The feasibility of irrigation and subsurface drainage systems must also be examined from the social point of view. This is particularly true in developing countries where irrigation and drainage projects are undertaken to change the livelihood of the local communities and the region at large.

This book covers irrigation and subsurface drainage fundamentals, systems, and impacts. Chapters 2, 3, 4, 5, 6, 7, 8, 9, 10 and 11 review basic principles and system components. Chapters 12, 13, 14, 15, 16, 17, 18, 19, 20, 21 and 22 focus on design of sprinkler, drip, surface, and bubbler irrigation systems. Chapters 23, 24, 25, 26, 27, 28, 29, 30 and 31 focus on wastewater, soils, nutrients, and subsurface drainage systems (Chaps. 23, 24, 25, 26, 27, 28, 29, 30 and 31). One of the strengths of this book is that almost all of the chapters have associated VBA/Excel programs. The programs enable students to evaluate realistic scenarios in homework problems and to more readily translate the knowledge and techniques in this book to the real world.

History of Irrigation and Subsurface Drainage

Irrigation and civilization have gone hand in hand. Beginning 8000 years ago, the Ubaid and then the Sumerians in Ancient Mesopotamia invented civilization and intensive irrigated agriculture at the same time. Regional canals delivered water from the Tigris and Euphrates rivers to large-scale irrigation systems and farms. Cities had between 50,000 and 80,000 people, with almost 90 % of the people living in the cities. Almost half of the population worked on the large irrigated farms (Fig. 1.1) surrounding each city. With modern agricultural methods, only 1 % of the population can now feed the rest of the population.

The importance of regional canals in Mesopotamia is evident in a statement by the famous Babylonian king Hammurabi (1750 BC):

> When Anu and Bel (gods) gave me the land of Sumer and Akkad to rule,. . . I dug out the Hammurabi-canal named Nuhus-nisi. Both the banks thereof I changed to fields for cultivation, and I garnered piles of grain, and I procured unfailing water for the land. As for the land of Sumer and Akkad, I collected the scattered peoples thereof, and I procured food and drink for them. In abundance and plenty I pastured them, and I caused them to dwell in peaceful habitation.

P. Waller, M. Yitayew, *Irrigation and Drainage Engineering*, DOI 10.1007/978-3-319-05699-9_1

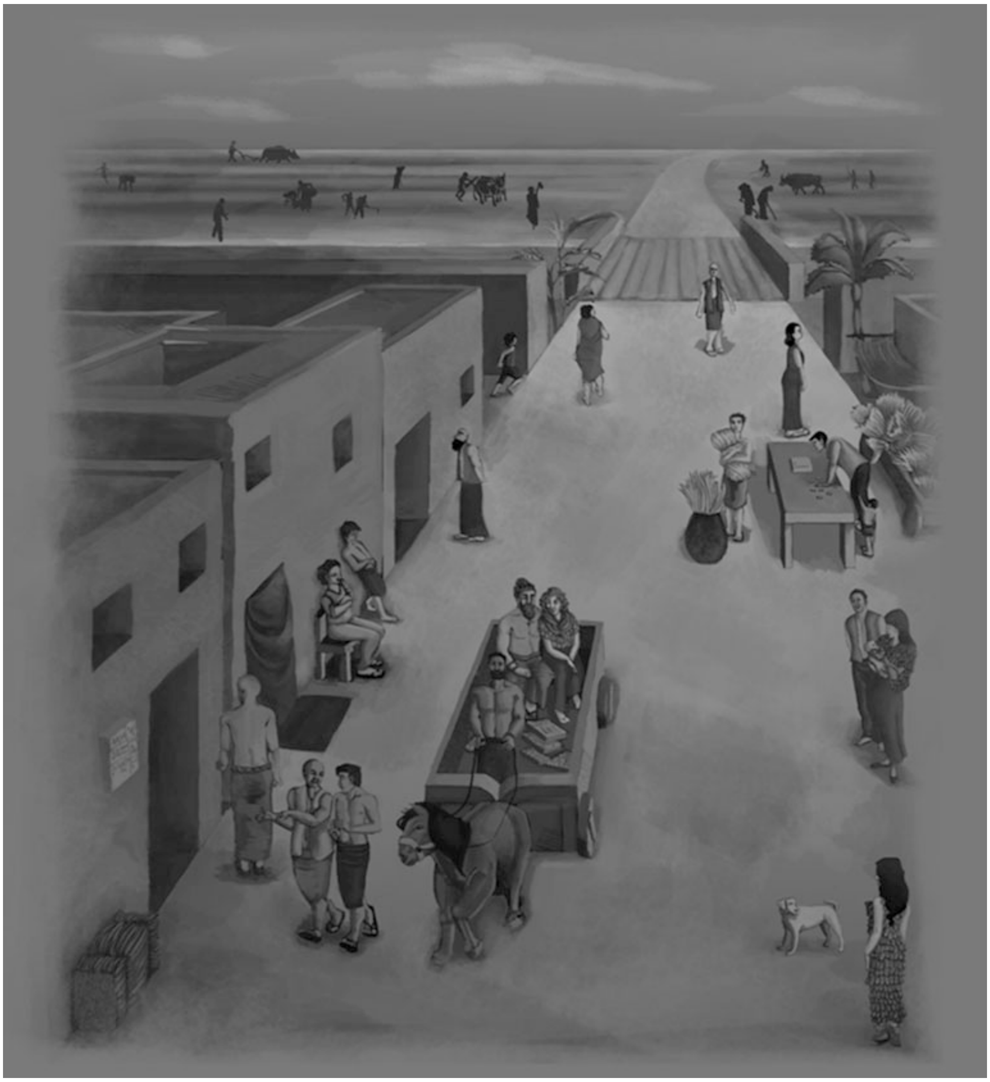

Fig. 1.1 Sumerian city with canal and surrounding farms (Credit Mariah Dunn, University of Arizona)

Not only were the canal systems remarkable, but the management of irrigation at the farm scale was also technologically advanced, as described in the following selected excerpts from the *Sumerian Farmer's Almanac* (1700 BC, translated from cuneiform by Samuel Kramer):

> In days of yore a farmer instructed his son: When you are about to take hold of your field (for cultivation), keep a sharp eye on the opening of the dikes, ditches, and mounds, (so that), when you flood the field the water will not rise too high in it. When you have emptied it of water, watch the field's water-soaked ground that it stay virile ground for you... plow diagonal furrows where you have plowed straight furrows, (And) Plow straight furrows where you have plowed diagonal furrows. Let your straight furrows make your borders into *tulu*-borders; let the *lu*-furrows make straight your borders. Plow *ab*-furrows where.... (Then) Let all its clods be removed; all its high spots be made into furrows; (and) all its depressions be made into low furrows... When the barley has filled the narrow bottom of the furrow, water the top seed. When the barley stands up high as (the straw of) a mat in the middle of a boat, water it (a second time). Water (a third time)-its royal barley. If the watered barley has turned red, what you say is: "It is sick with the *samana*-disease." But if it has succeeded in producing kernel-rich barley, water it (a fourth time); (and) It will yield you an extra measure of barley in every ten (+10 %)...

We can see the importance that the Sumerians placed on straight furrows, proper maintenance of dikes and ditches, leveling, borders and basins, crop monitoring, and irrigation scheduling. Nothing has changed. Irrigation engineers and managers must still pay careful attention to the design and maintenance of their irrigation systems. Farmers must manage water effectively. As stated in the *Almanac*, yield might be increased by 10 % with optimal irrigation management.

The Sumerian culture vanished from Sumer in 2350 BC. This took place at the same time that the soil became salinized. The Sumerians returned to Sumer in 2055 (short

Fig. 1.2 Diversion structure (Dujiang Weir) for Dujiangyan irrigation system. "Dujiang Weir." (Credit: Huowax at zh.wikipedia)

chronology) and formed the Third Dynasty of Ur for approximately 100 years. Evidence of the salinization is found in cuneiform agricultural records, which report that grain yields in 2400 BC were 2347 L/ha, but production dropped to 1460 L/ha in 2100 BC. Yields then dropped even further to 900 L/ha in 1700 BC. Another indication of salinization is that 80 % of the grain percentage was barley in 2400 BC, but it rose to 99 % barley in 2050 BC.[1] Barley is a salt tolerant crop and is often the first crop used to reclaim saline desert soils for agriculture. A higher percentage of barley in the crop mix indicates soil salinization.

The Egyptians learned about intensive agriculture from the Sumerians. Their irrigation was dependent on the annual flooding of the Nile, which had a different and more predictable annual flood pattern than the Tigris and Euphrates. The water in the Nile covered the Nile floodplain with 1.5 m of water in September and remained for approximately 1 month. Once the fields were dry in November, the farmers planted a winter wheat crop and then harvested the crop in April and May. If necessary, they built basins to impound the water until fields were fully saturated and then allowed the water to drain away. Because the water table was 3–4 m below the ground surface just before the floods, the floodwaters pushed the salts out of the root zone each year.

The Indus River annual flow is three times larger than the Nile River and 10 times larger than the Colorado River. The Indus Valley Civilization (3300–1300 BC) was the largest in the ancient world, with up to five million people. The civilization had small villages with irrigated farms, which produced barley, wheat and other crops. They built extensive irrigation canals and other hydraulic systems such as sewage networks. Much of the civilization collapsed in 1800 BC, possibly due to drought caused by a decrease in monsoon activity in the region. The current Indus River Irrigation System irrigates 16.2 million hectares, which makes it the largest irrigation system in the world.

The Yellow River in China is another cradle of civilization and water management. Hydraulic engineer Zheng-Guo developed a successful irrigation canal network that was fed by a tributary of the Yellow River. The irrigation system enabled the development of 200,000 irrigated acres in Qin province in 246 BC. The system had a main canal and many lateral distribution canals. At the same time, the Qin Dynasty developed the Dujiangyan irrigation system, which is still in use and currently irrigates 5,300 square kilometers. The diversion structure for the Dujiangyan is shown in Fig. 1.2. The plentiful food supplies from irrigated farms and resultant population growth enabled the Qin Dynasty to unify China under its leadership.

Although not well-known outside the Middle East, if you asked a Middle Easterner about major water resource projects in history, then they would immediately think of the Wadi Marib Dam in South Yemen, which is at the southern end of the Arabian Peninsula. It was a triangular structure constructed of packed earth. It was originally 4 m tall and 580 m long in 1700 BC. The height was increased to 7 m and rock was placed on the upstream side in 500 BC, and a sluiceway was constructed for overflow on the side. The Sabean civilization (Kingdom of Sheba) thrived there for over a millennium. The region was taken over by the Himyarites in 115 BC, and they increased the height of the

---

[1] Altaweel and Watanabe (2012).

Fig. 1.3 Artist's rendition of Hohokam irrigation system (Credit USBR. Artist Peter Hurd)

dam to 14 m and added five spillway channels, two sluices, and a 2 mile channel to a holding tank by 325 AD. At this time, the dam irrigated 100 km^2 in the Marib Plain. The dam was breached and repaired several times after 500 AD, but it was left unrepaired in 570 AD. As a result, 50,000 people were forced to migrate from the region. A new triangular dam has now been reconstructed at a different location in the Wadi Marib.

Native Americans constructed irrigation systems in the southwest United States. One of the most famous was the Hohokam (Fig. 1.3) irrigation network in the Phoenix, Arizona area. The Hohokam civilization lasted hundreds of years, but it was destroyed by an extended drought in thirteenth century AD.

The prehistoric Owens Valley Paiute in California had the most extensive Native American irrigation system. They had a main canal that was several miles long and many small branch canals. Each year they built a new diversion dam in the Owens River with boulders, sticks, and mud in order to divert water into the canal. The Owens River became the focus of one of the most famous battles in water history as Director Mulholland of the Metropolitan Water District in Los Angeles bought out the water rights of Owens Valley farmers (not the original Native American farmers) and ended agriculture in the Owens Valley. This battle between Los Angeles and farmers is described in the book *Water and Power*.

In 1933, a citrus grower in Los Angeles, California named Orton Engelhart invented and patented the impact sprinkler: The family that formed Rain Bird purchased the patent, and the rest is history. Drip irrigation was invented in Israel in the 1950s and 1960s. After these major developments in pressurized irrigation, irrigation companies have continued to refine these basic irrigation technologies in order to reduce cost and improve reliability, uniformity, and efficiency.

Irrigation expanded dramatically in the last century. As the world's population increased, improved food production methods were needed to prevent mass starvation. Along with improved plant varieties and fertilization, irrigation was one of these three reasons for a dramatic increase in world food production. Seventy percent of the world's food is now produced by irrigated agriculture. Many of the rivers in the arid and semiarid western United States (Fig. 1.4) were dammed and used for irrigation. Another example of the impact of irrigation was the Green Revolution in India in the early 1970s. Prior to the Green Revolution, large-scale famines had followed droughts in India. The introduction of dams and irrigation made double-cropping possible. Fed by new dams and irrigation districts, irrigated farms were able to supply the country with adequate food. A recent survey by the International Committee on Irrigation and Drainage found that there are almost 300 million ha of irrigated acreage in the world.

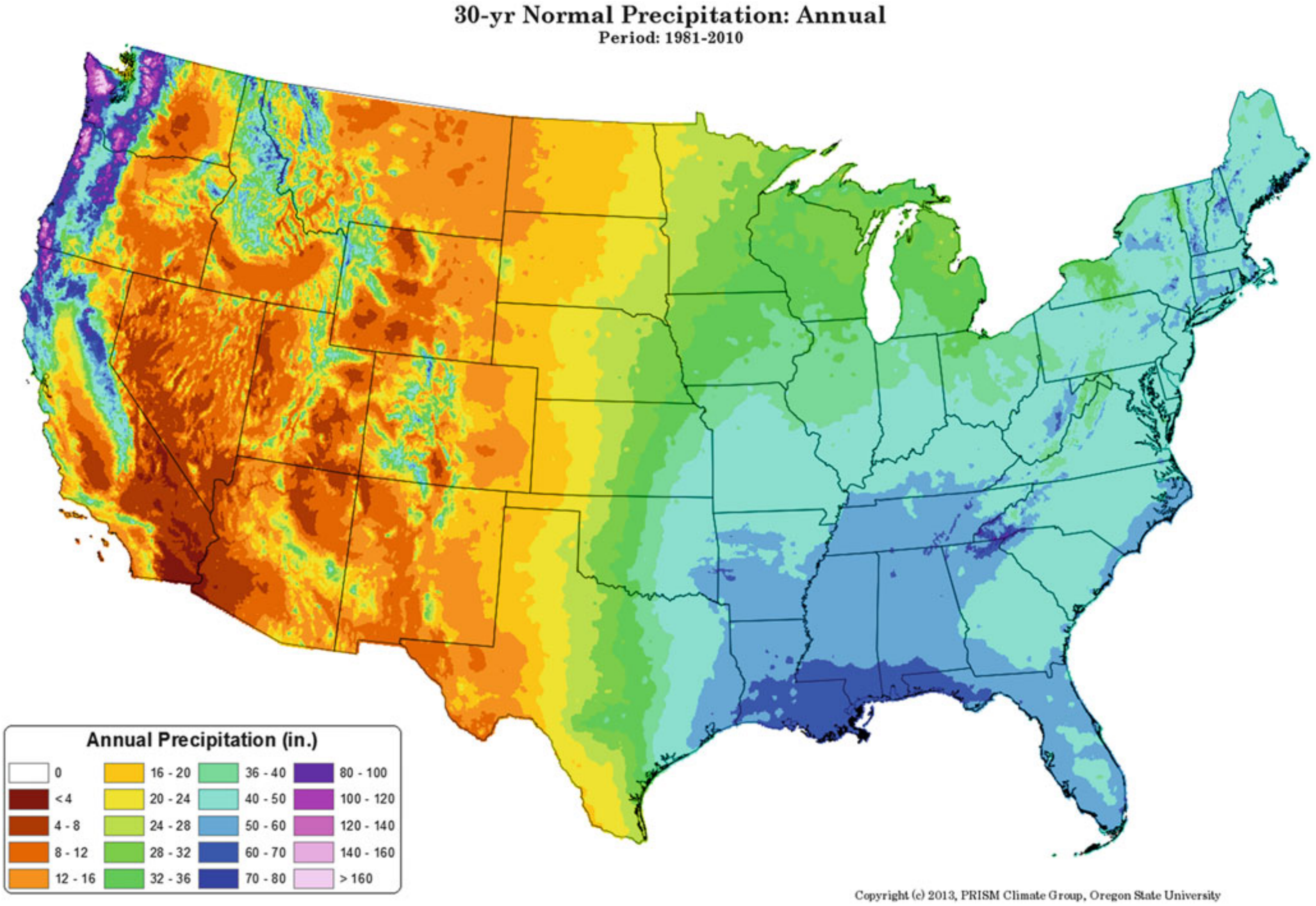

Fig. 1.4 Rainfall patterns in the United States (Credit http://www.prism.oregonstate.edu/normals/ *Work was performed under NRCS contract*)

On the other side, subsurface drainage has been used extensively to drain wetlands and build farms. In the past, "swamps" or "badlands" were considered useless. For example, the goal of the US government was to drain the swamps and convert the land to farms. The government drained wetlands, built levees along rivers, and encouraged the drainage of "swamps" with the Swamp Acts of 1849, 1850, and 1860: swamps were given to any states or private individuals who were willing to drain them. In the 1970s, scientists realized that the loss of wetlands had drastic consequences for the environment. Now, the US government has reversed course. It changed its policy from draining every swamp to protecting even the smallest puddle on a farm. The government is backpedaling as fast as it can in order to preserve, protect, rebuild, and replace wetlands, which are the base of the food web. Wetlands also contribute to the global carbon, nitrogen, water, and sulfur cycles. Wetlands are the breeding ground for 80 % of America's birds, and they are important rest stops for migratory birds. Two-thirds of all birds in the United States reproduce in prairie pothole wetlands. Almost all commercially harvested fish and shellfish are in some way dependent on wetlands. Wetlands also prevent floods by storing flood water during storms. They remove pollutants and sediments from water before they enter rivers. Because of their ecological benefit, areas such as the prairie pothole wetland shown in Fig. 1.5 are now protected and cannot be drained.

It appears that global warming, with its associated droughts and floods, is throwing off previous hydrologic models and design strategies. Rainfed agriculture in some regions is increasingly subject to water stress. Irrigation water allotments, which depended on calculated river flows or groundwater recharge rates may need to change. For example, the Colorado River irrigates 3.5 million acres in the southwest US. These farms produce enough food for 25 million people. The Colorado River was already over allocated because hydrologic studies that were the basis of the legal division of water between western states and Mexico were conducted during a period of higher than normal precipitation. Although some states have yet to require their full allocation of Colorado River water, this period of underutilization by some states is ending with

Fig. 1.5 Prairie pothole wetland on Montana farm (Credit EPA, photo by Dr. Richard Hauer)

population growth and increased water demand in the Southwest. The current severe droughts in California and the Colorado River basin have depleted reservoir levels to historic lows. Water is being cut back in many regions, and farms water allocations are being cut off. Only time will tell whether these droughts are a sign of climate change and whether permanent changes are needed.

One of the most important concepts in water resources development is sustainability. The basic premise of sustainability is that natural resources should not be depleted over time but should continue to provide the same benefit in perpetuity. Sustainability has been defined by law in many states as a 100-year supply of water. With respect to groundwater resources, the rate of extraction from an aquifer should not exceed the rate of aquifer recharge.

If not regulated, water resources naturally become stretched beyond their capability to supply demand. As people begin to develop irrigated farms in a region, well drilling is generally not regulated; thus, the rate of pumping soon exceeds the rate of recharge in a successful farming region. As the groundwater table recedes to hundreds of feet below the ground surface, the cost of pumping increases, and the aquifer yield decreases until farmers eventually start going out of business. As the situation becomes dire, one possible option is that the government might build a canal and deliver water to the region. Another strategy is to take control of the groundwater and not allow excessive pumping. This strategy was employed in Arizona. In 1980, government, agriculture, municipal, mining, and business leaders joined together and developed the Groundwater Management Act, which limited water use by all the entities in the state. Under this plan, no construction of new farms in affected regions is allowed, and water conservation measures are rewarded. Another example of this type of aquifer degradation is the giant Ogallala aquifer, which covers eight states in the High Plains region of the United States. This southern part of the aquifer has been over-pumped for irrigation; and the water table is now so far below the surface that it is no longer economical for many farmers to extract water.

In some cases, over-pumping of aquifers is planned. For example, in the Central Valley of California, planners purposely allowed over-pumping in order to develop the local economy. They calculated correctly that the region, after development, would then have adequate monetary resources to pay for a canal system to deliver water from the Sacramento River.

With the onset of global warming, even water resource systems that were considered sustainable may not be sustainable. Climate models indicate that global warming will cause droughts in some parts of the world. Regions with rain fed agriculture may need to construct irrigation systems, and regions with inefficient irrigation systems may need to increase efficiency. Drainage systems that formerly removed most of the water from spring rains may need to be modified or abandoned. Areas with increased precipitation may need to add additional drainage infrastructure. These types of changes might provide many jobs for irrigation and drainage engineers.

Foundational Principles (Chaps. 2, 3, 4, 5, 6, 7, 8, 9, 10 and 11)

As with the Sumerians, today's engineers and water managers must pay careful attention to their soils, crops, and irrigation technologies in order to maximize production. The next ten chapters cover the fundamental principles and skills required by irrigation and drainage engineers. Knowledge of soils, crop water demand, salinity and water stress, irrigation design principles, pipes, pumps, groundwater, and channels should all be a part of the irrigation and drainage engineer's toolbox.

Decisions are ultimately based on economics. What type of irrigation system and management style will result in the greatest profit for the farmer? Chapter 2 provides a general introduction to irrigation economics, which enables the evaluation of irrigation alternatives based on capital cost and annual costs and benefits. Topics include crop water production functions, which quantify the relationship between depth of water applied and crop yield, and equations for calculating water, energy, and environmental costs.

The next four chapters describe soil physics, crop stress, and crop water demand. Chapter 3 reviews soil water holding capacity, infiltration rate, root zone depth, soil moisture measurement devices, and the relationship between water content and matric potential. Chapter 4 shows how to calculate yield reduction in response to salinity and water stress.

Chapter 5 describes the theory and use of the Penman-Montieth evapotranspiration model. It also includes a program that makes these calculations and automatically downloads weather information from weather stations. Chapter 6 shows how to convert reference evapotranspiration to the evapotranspiration rate for any crop. The crop coefficient is the ratio between crop evapotranspiration and reference evapotranspiration. The dual crop coefficient approach from FAO 56 separates soil evaporation and plant transpiration. The heat unit method calculates the crop coefficient as a function of time and temperature since planting rather than just time since planting

The final five chapters of this section cover the nuts and bolts of irrigation: pipes, pumps, groundwater and wells, and channels. Chapter 7 shows how to design a sprinkler irrigation lateral. Hydraulic equations are used to determine the change in pressure along the pipeline, and statistics are used to generate an application rate distribution along the pipeline. Monte Carlo analysis is used to evaluate the effects of pipe diameter, water cost, energy cost, water application distribution, and crop yield on overall profit. Chapter 8 describes pipe friction and minor losses, energy diagrams, pipe pressure rating, and pipe transients (water hammer). Chapter 9 describes types of pumps, affinity laws, use of pump curves, and the intersection point of the pump curve and the system curve. Chapter 10 describes aquifer types, characteristics, parameters, equations, and classifications. Although irrigation engineers are generally not experts in groundwater hydrology, an introduction to groundwater and wells is helpful as engineers interact with groundwater and well professionals. Both transient and steady state analysis methods are presented. Chapter 11 familiarizes students with the fundamentals of canal and ditch design. Topics include diversion structures, delivery structures, flow measurement structures, conveyance efficiency, Manning's equation, surface roughness, channel sections, uniform flow, varied flow, and Froude number. All of the chapters include VBA/Excel programs that perform the calculations described in the chapters. Homeworks include manual calculations and use of the VBA/Excel programs.

Irrigation Systems (Chaps. 12, 13, 14, 15, 16, 17, 18, 19, 20, 21 and 22)

Contrary to popular belief, there is no such thing as a "best" irrigation system. The selection of an irrigation system is based on soil, crop, economics, water quality, and management considerations. The Natural Resources Conservation Service (NRCS) *National Engineering Handbook* (NEH) describes the four major irrigation methods: surface, sprinkler, micro, and subirrigation.

1. ***Surface***—*Water is applied by gravity across the soil surface by flooding or small channels (i.e., basins, borders, paddies, furrows, rills, corrugations)*
2. ***Sprinkler***—*Water is applied at the point of use by a system of nozzles (impact and gear driven sprinkler or spray heads) with water delivered to the sprinkler heads by surface and buried pipelines, or by both. Sprinkler irrigation laterals are classed as fixed set, periodic move, or continuous or self move. Sprinkler irrigation systems include solid set, handmove laterals, sideroll (wheel) laterals, center pivot, linear move (lateral move), and stationary and traveling gun types. Low Energy Precision Application (LEPA) and Low Pressure In Canopy (LPIC) systems are included with sprinkler systems because they use center pivots and linear move irrigation systems.*
3. ***Micro***—*Water is applied to the point of use through low pressure, low volume discharge devices (i.e., drip emitters, line source emitters,, micro spray and sprinkler heads, gravity and low pressure bubblers) supplied by small diameter surface or buried pipelines.*
4. ***Subirrigation***—*Water is made available to the crop root system by upward capillary flow through the soil profile from a controlled water table. Each irrigation method and irrigation system has specific site applicability, capability, and limitations.*

The relative frequencies of irrigation system types (1997) in the United States are shown in Fig. 1.6. The United States as a whole and the states with largest amount of irrigated land area have a relatively even mix of pressurized and surface irrigation systems. The states with a small irrigated land area tend to exclusively use pressurized irrigation. In 1997, the only state that was almost entirely surface irrigated was Arizona; however, center pivots and drip irrigation have become more popular in recent years in Arizona. In spite of the increasing popularity of pressurized irrigation, the hundreds of thousands of irrigated acres that have been developed by Native American communities in Arizona in recent years are almost entirely surface irrigated. The selection of surface irrigation was driven partially by the fact that the Native American communities have surface irrigated their fields for hundreds, possibly thousands, of years. The other factor was that they installed highly efficient level basin systems that were paid for by the government. With their large flow rates, the water moves quickly across the field, and all parts of the field receive approximately the same depth of water. This type of decision that is driven by past experience and comfort with a certain technology is common among farmers. Many farmers are reluctant to change to new technologies. In many cases they are wise not to change because may be unknown pitfalls associated with new technologies. On the other hand, if other farms adopt technology that enables them to produce higher quality and lower cost food, then the farmers that did not adopt the new technology may be left behind.

One of the primary drivers in irrigation system selection is crop type. For example, vegetable crops cannot be

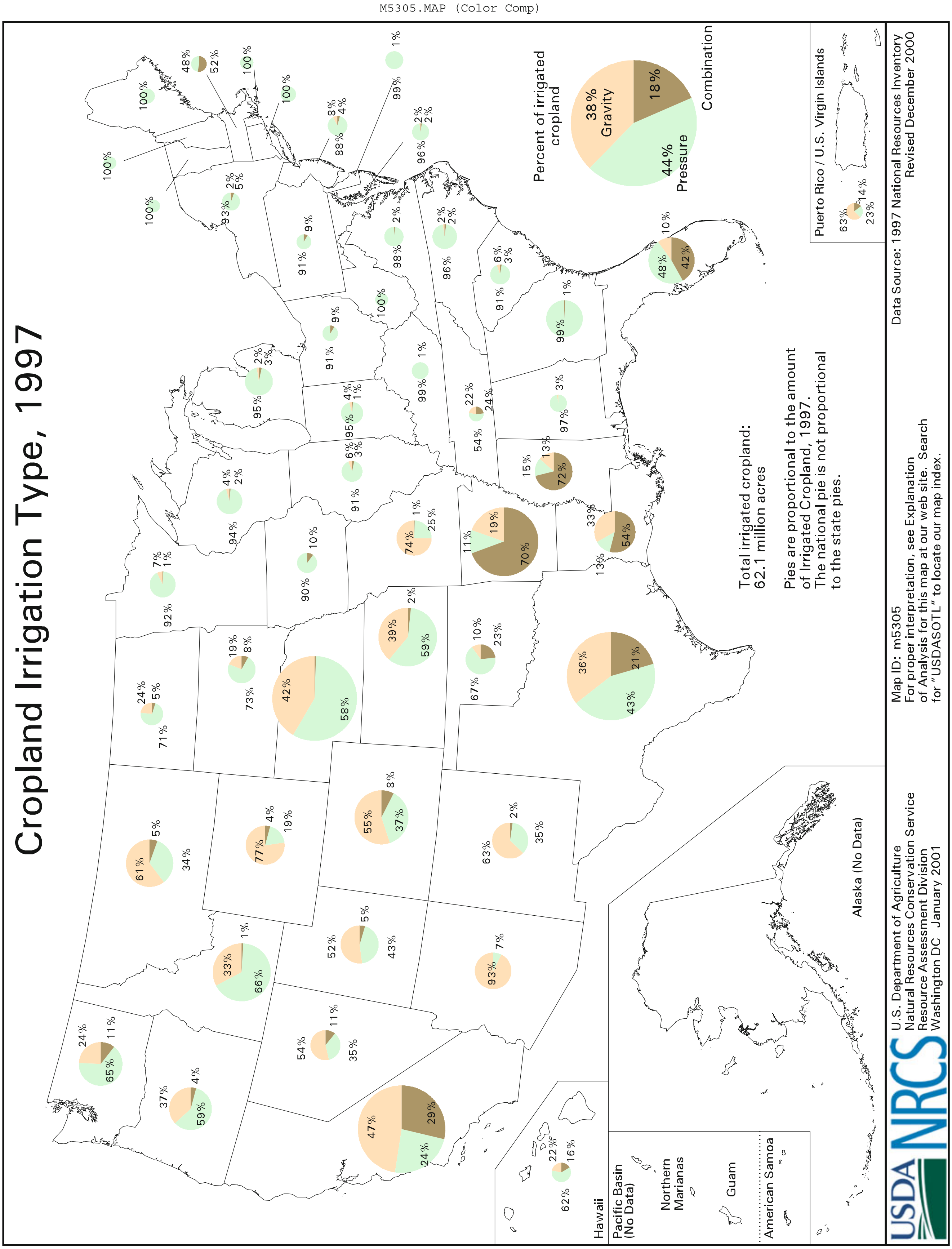

Fig. 1.6 Distribution of irrigation systems in the United States (Credit NRCS NEH)

Table 1.1 Acceptable irrigation systems for crop categories (Credit NRCS NEH Part 652 Ch 3)

	Crop category			
Irrigation system	1	2	3	4
Surface				
Basins, borders		x	x	x
Furrows, corrugations	x	x		x
Contour levee – rice		x	x	
Sprinkler				
Side (wheel) roll lateral	x	x		
Hand move lateral	x	x		x
Fixed (solid) set		x		x
Center pivot, linear move	x	x		
Big guns – traveling, stationary	x	x		
Micro				
Point source				x
Line source	x			x
Basin bubbler				x
Mini sprinklers & spray heads				x

flooded. The *NRCS NEH* (652- Ch. 3) divided crops into four general categories and defined the acceptable irrigation methods for each crop category in Table 1.1:

Category 1. *Row or bedded crops: sugar beets, sugarcane, potatoes, pineapple, cotton, soybeans, corn, sorghum, milo, vegetables, vegetable and flower seed, melons, tomatoes, and strawberries.*
Category 2. *Close-growing crops (sown, drilled, or sodded): small grain, alfalfa, pasture, and turf.*
Category 3. *Water flooded crops: rice and taro.*
Category 4. *Permanent crops: orchards of fruit and nuts, citrus groves, grapes, cane berries, blueberries, cranberries, bananas and papaya plantations, hops, and trees and shrubs for windbreaks, wildlife, landscape, and ornamentals.*

The crop, soil, water, and climate parameters that should be considered in irrigation selection are listed in Table 1.2. In practice, each agricultural region settles on one or two primary irrigation methods that have proven successful. As an irrigation engineer, I developed a guiding principle: never be the first person to install a new irrigation product in a region, at least don't commit an entire farm to a new irrigation technology, no matter what the product representative claims. The potential pitfalls are unknown because each region is unique, and if the entire farm is committed to an irrigation system that does not work, then there are severe economic consequences. Try out new technologies on small plots and work out the bugs, if possible, on a small scale. In this way, an unforeseen technology failure will not bankrupt the farm. Most farmers have the same level of caution about new products.

Table 1.2 Site considerations in selecting an irrigation method (Credit NRCS NEH. 652 Ch 5)

Crop	Soil	Water	Climate
Crops grown and rotation Water requirement Height Cultural practices Pests Tolerance to spray Toxicity limitations Allowable MAD level Climate control Frost control Cooling Diseases and Control Crop quality Planned yield	AWC Infiltration rate Depth To water table To impervious layer Drainage Surface Subsurface Condition Uniformity Stoniness Slope Surface texture Profile textures Structure Fertility Temporal properties	Quality Salts, toxic elements Sediment Organic materials Fish, aquatic creatures Quantity Reliability Source Stream Reservoir Well Delivery point Delivery schedule Freqency Duration Rate	Wind Rainfall Frost conditions Humidity Temperature extremes Rainfall Evaporation from: Plant leaves and stems Soil surface Solar radiation

The ways in which the parameters in Table 1.2 influence irrigation system selection are described in the NRCS NEH (Part 652. Ch. 6):

- ***Surface systems***. *High sediment laden irrigation water generally reduces intake rates, which on coarse textured soils may increase advance rates thereby improving distribution uniformity for the field. On medium and fine textured soils, a reduced intake rate may be undesirable.*
- ***Graded furrow systems***. *On furrow slopes greater than 1 percent and on highly erodible soils, erosion rates can be severe unless protective measures are provided.*
- ***Level basin and graded border systems***. *Larger heads of water are required to meet minimum flow depth requirements in a level basin or border (typically 5 to 7 cubic feet per second) and maintain reasonable field sizes. High uniformity can be attained with level basins on medium and low intake rate soils.*
- ***Sprinkler***. *Low pressure continuous/self move center pivot and linear systems — requires intense water, soil, and plant management for low intake soils, and at least a moderate amount of management on low to medium intake soils.*
- ***Micro***. *Water quality must be high except for basin bubbler systems, which use plastic tubing of 3/8 inch diameter and larger. Chemicals must be used to prevent algae growth in most systems.*

Irrigation efficiency has been defined in many ways. In general, efficiency is the amount used divided by the amount applied; however, irrigation efficiency can be thought of in different ways. Conveyance efficiency is the amount of

Table 1.3 Potential efficiencies of agricultural irrigation systems (Solomon 1988)

Irrigation system	Potential on-farm efficiency
Gravity (Surface)	
Level basin	80–90 %
Furrow	65–75 %
Border	70–85 %
Sprinkler irrigation	
Hand move or portable	65–75 %
Side roll wheel line	65–75 %
Traveling big gun	60–70 %
Center pivot	75–90 %
Linear move	75–90 %
Solid set or permanent	70–80 %
LEPA	80–95 %
Microirrigation	80–90 %

water reaching a field divided by the amount diverted from the irrigation water source. Application efficiency is the amount of water stored in the root zone divided by the amount of water applied to the field. Storage efficiency is the amount of water stored in the root zone during a single irrigation divided by the total water-holding capacity of the root zone. Seasonal irrigation efficiency is the water volume beneficially used by the crop (including leaching) divided by the seasonal amount of water applied.

In general, pressurized irrigation systems (sprinkler and micro) are assumed to have higher application efficiencies than surface irrigation systems. However, loss of water by evaporation or wind, poorly maintained sprinklers or emitters, and poor uniformity due to spacing or pipe hydraulics decrease application efficiency. Surface irrigation system application efficiency is decreased by variation in soil permeability and by variation in ponding time across the field. Runoff also decreases efficiency for surface irrigation systems; however, if a water recycle and reuse system is in place, then runoff generally does not result in a loss of efficiency at the farm scale. At the irrigation district scale, even major losses to leaching and runoff, are generally recycled in the irrigation district as a whole. Thus, improving irrigation efficiency does not necessarily result in an improvement in water use efficiency at the irrigation district scale. Potential application efficiencies for different irrigation systems are shown in Table 1.3.

Sprinkler Irrigation (Chaps. 12, 13 and 14)

These chapters describe five types of sprinkler systems: center pivot, turf, wheel-line and hand-line, orchard, and microsprinkler irrigation. Sprinkler irrigation systems have two major advantages over surface irrigation systems. First, the field does not need to be leveled or graded. In fact, steep slopes can increase uniformity if pipe sizes are selected such that pipe friction loss equals elevation gain (pressure remains constant). Second, if there is no runoff or ponding, then variation in soil properties does not influence sprinkler application uniformity. One of the disadvantages of sprinkler irrigation, especially in arid regions, is evaporation and wind drift before the droplet reaches the soil.

Although 94 % of irrigation in the world is surface irrigation, sprinkler irrigation accounts for 46 % of irrigated acreage in the United States. The major reason for this large percentage is the popularity of center pivots. 75 % of sprinkler-irrigated land in the United States is under center pivot irrigation. Center pivot irrigation began in Nebraska and now waters 4.6 million out of 7 million acres of irrigated agriculture in Nebraska. Considering capital, labor, energy, and water cost, center pivots are generally the most inexpensive way to water row crops and pasture. The major design constraint is that the application rate at the outer end of the pivot cannot exceed the sum of soil infiltration rate and the surface water storage. Otherwise, runoff occurs and application uniformity decreases. Center pivots consist of a steel pipe and truss system that is connected to the water source at the pivot point. They generally use electric power to drive tractor tires that move the structure through the field. Most center pivots water a quarter section (50 ha or 160 acres). Center pivots rotate in a circle around a central pivot point (Fig. 1.7); however, linear move irrigation systems (Fig. 1.8) travel along a straight line and are guided by cables at each end. Chapter 12 describes the sprinkler and pipe calculations for center pivot irrigation. It also includes a VBA/Excel program that calculates sprinkler orifice sizes, pipe diameter, and application uniformity for center pivots.

Turf irrigation has become an important sector of the irrigation industry. Turf irrigation systems (Fig. 1.9) water vegetation that is not sold for profit. Thus, the criteria for turf irrigation management are different than for agricultural irrigation management. For example, a management goal might be that there are no brown spots on a golf course. In this case, the location with the minimum application rate governs the application time of the sprinkler zone. With this in mind, the turf sprinkler industry recommends the scheduling coefficient (average depth applied over minimum depth applied) to evaluate application efficiency. Chapter 13 describes the methods to calculate sprinkler spacing, sprinkler uniformity, pipe design, and the scheduling coefficient. The *Sprinkler Uniformity* program is used to calculate uniformity as a function of sprinkler spacing and sprinkler characteristics.

Chapter 14 describes four types of agricultural sprinkler systems: wheel-lines, hand-lines, undertree sprinklers, and microsprinklers. Hand-lines and wheel-lines (Fig. 1.10) are generally used to water row crops and pasture. Hand lines are small (2–3″ diameter, 50–75 mm) aluminum sprinkler

Fig. 1.7 Center pivot irrigation systems (Credit NRCS)

Fig. 1.8 A canal-sourced linear-move irrigation system in use on a field in Colorado (Credit: GE Cardon, Bugwood.org)

Fig. 1.9 Turf irrigation system (Credit NRCS)

Fig. 1.10 Hand-line and wheel-line (Credit NRCS)

pipes. For crop germination (left side, Fig. 1.10), the hand-line system waters the entire field at one time. For irrigation of established row crops or pasture, single lines of sprinklers are moved once or twice per day and rotated through the field. Similarly, wheel-lines are moved once or twice per day; however, instead of moving the pipes by hand, a small motor rotates the pipeline and wheels.

The *Sprinkler Uniformity* program introduced in Chap. 13 is used in Chap. 14 to develop application distributions for wheel-line and hand-line systems. The calculated spatial distribution statistics are combined with hydraulic calculations of sprinkler flow rate along the pipeline to calculate an overall water application distribution for the entire pipeline.

Undertree orchard sprinklers have a low spray angle so that the stream does not hit the canopy. The primary orchard sprinkler design parameters are application rate (must be less than infiltration rate), number of zones, sprinkler spacing, sprinkler flow rate, and pump selection. Orchard sprinkler spacing is constrained by the fact that trees have a fixed spacing, and sprinkler spacing must be a multiple of tree spacing.

Landscape Irrigation (Chaps. 15 and 16)

Landscape irrigation systems water trees and shrubs in urban landscapes. Two of the primary methods are drip irrigation and bubbler irrigation. The unreliability of single barbed emitters inserted into polyethylene pipe (the conventional method) has led to adoption of more reliable technologies such as in-line drip systems (Fig. 1.11), multiport emitters mounted on PVC pipe, and bubbler systems. Chapter 15 also describes the control zone components: solenoid valves, controllers, valve boxes, pressure regulators, and backflow preventers.

In addition to problem of unreliability, a second problem with most landscape irrigation systems is that homeowners and landscape professionals generally cannot adjust the watering schedule to match the plant evapotranspiration requirements. In addition, they rarely adjust the number of emitters per plant as plants grow. Chapter 16 presents calculation procedures for irrigation schedules and number of emitters per plant. In addition, the *Landscape* program calculates the number of emitters or bubblers required for each plant in an irrigation zone as well as the watering schedule. With the many types and sizes of plants in an irrigation zone, this program is helpful for achieving uniformity in a landscape zone. The program uses the landscape coefficient method to calculate the water requirement of each plant.

Fig. 1.11 Line source in-line drip irrigation tube for landscape irrigation with the emission point near the middle of the picture

Agricultural Drip Irrigation (Chaps. 17, 18 and 19)

Drip irrigation does not represent a large fraction of irrigation systems in the world; however, many new irrigation systems are drip systems. Thus, many irrigation companies focus on drip irrigation system design. One of the most popular applications of drip irrigation is the irrigation of vineyards, where the drip tube is hung from the trellis (Fig. 1.12).

With relatively thin polyethylene laterals and small orifices (Fig. 1.13), drip systems are more fragile than sprinkler, bubbler, or flood systems; thus, drip irrigation systems require a high level of management expertise. Systems may require sand filtration of particulates, chlorination to prevent bacterial growth, acid injection to prevent calcium carbonate

Fig. 1.12 Vineyard drip irrigation system on trellis (Credit NRCS)

Fig. 1.13 Drip emitter and polyethylene tubing hanging from trellis wire (Credit NRCS)

deposition, and regular flushing to remove sediment from drip laterals. Although drip irrigation generally requires a higher level of management expertise, it is growing in popularity for several reasons. One reason is that it maintains a relatively constant level of moisture in the root zone, which increases production of many crops. A second reason for the increasing popularity of drip irrigation is that the potential efficiency (90 %) is greater than for other irrigation systems. Evaporation from the soil surface is dramatically reduced or may be zero for subsurface drip irrigation. Drip irrigation systems are also effective chemigation systems because they apply water directly to the plant root zone.

Subsurface drip irrigation is the most widely used drip irrigation method. In order to protect the drip tubing from cultivation practices, laterals are buried approximately 15 cm below the ground surface (Fig. 1.14). Some of these systems have lasted 15 or more years without replacement of the inline tubing. Reliability depends on management expertise, wall thickness, and soil type. Extremely thin wall tubing might be plowed into the soil each year. Tillage implements and GPS systems have been designed that maintain the bed over the tubing during cultivation practices so that the tubing is not disturbed and remains in the same position in the bed.

Chapters 17 and 18 describe how integrate the components and options in subsurface irrigation in a final design: emitter flow rate, lateral tubing length, lateral and emitter spacing, tubing diameter, submain and mainline diameters, flushing, the pump station, and sand filters. The design is analyzed with an economic analysis that includes pipe, tubing degradation, energy, environmental, and water costs, as well as the effect of spatial variation of water application on yield and water cost. The complex analyses are performed in a VBA/Excel program.

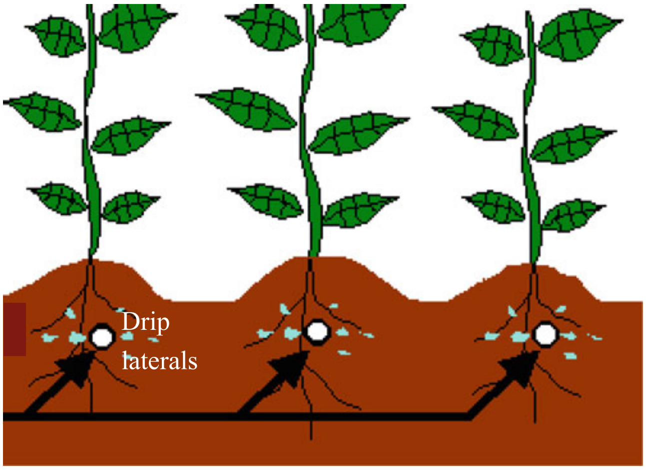

Fig. 1.14 Subsurface drip irrigation (Courtesy of Paul Colaizzi. USDA-ARS)

Chapter 19 describes chemigation injection systems. It describes calculation procedures for rates of acid injection, chlorination, fertigation, and pestigation. Acid injection rates are calculated as a function of the water alkalinity, acid strength, and the desired endpoint pH.

Surface Irrigation (Chap. 20)

Three of the most popular types of surface irrigation systems are sloping border, graded furrow (Fig. 1.15), and level basin – with furrow irrigation representing half of all surface irrigation systems. Other types include contour level furrows and corrugation irrigation. Many farms now use near-level furrows and borders as the best strategy to achieve high efficiency and uniformity. The four primary design parameters in surface irrigation systems are slope and length of the field (difficult to change), flow rate, and cut-off time. The optimization of these parameters can be performed with the USDA-ARS WINSRFR surface irrigation model. This chapter describes how the advance phase can be modeled with the two-point volume balance method. The infiltration phase is modeled with a numerical model of flow in a furrow that includes decrease in flow rate vs. distance and spatial variation of soil properties. Chapter 20 focuses on the use of the WINSRFR model in the design and analysis of furrow irrigation systems; however, the WINSRFR model has many other "Worlds" for the design of other systems and

Fig. 1.15 Furrow irrigation system in Arizona

applications. The model can also evaluate the effects of such things as leveling, which would have been of interest to the Sumerians.

Hydroponic Drip Irrigation Systems (Chap. 21)

Hydroponic drip systems are used in controlled environment agriculture (greenhouses). The operation and management of these systems is unique. Water is applied to a soilless growing media such as coconut husks, rock wool, sand, and/or perlite. These soilless media give growers the ability "steer" the crop toward desired production characteristics by rapidly varying nutrient and salinity concentrations in the media. The chapter describes the calculation methods for setting up a nutrient recipe for hydroponic fertigation. It also includes a VBA/Excel program for this task.

Low-Head Bubbler Irrigation (Chap. 22)

A system that is gaining in popularity in greenhouse and conventional agriculture is low-head bubbler irrigation. These systems have large openings so they never plug. They have extremely low pressure requirements so power costs are low. They require no specialized components such as emitters or sprinklers so capital costs are low. In these systems, tubing at each plant is cut to a precise length and installed to a precise elevation in order to provide the design flow rate to the plant.

Below the Surface of the Soil (Chaps. 23, 24, 25, 26, 27, 28, 29, 30 and 31)

The last chapters in this book focus on the fate of water, salinity, and nutrients in the soil. These chapters are augmented with the *WINDS* model (Water-use, Irrigation, Nitrogen, Drainage, and Salinity), which models the fate of water and solutes in the soil profile. The chapters describe the algorithms in the *WINDS* model and then use the model to visualize the processes in the soil. The *WINDS* model is also designed to be used in real-world applications. With quick set up and run time for design, evaluation, or management, it can be deployed in a few hours. The *WINDS* model can simulate up to 12 soil layers and over 1,000 field locations;

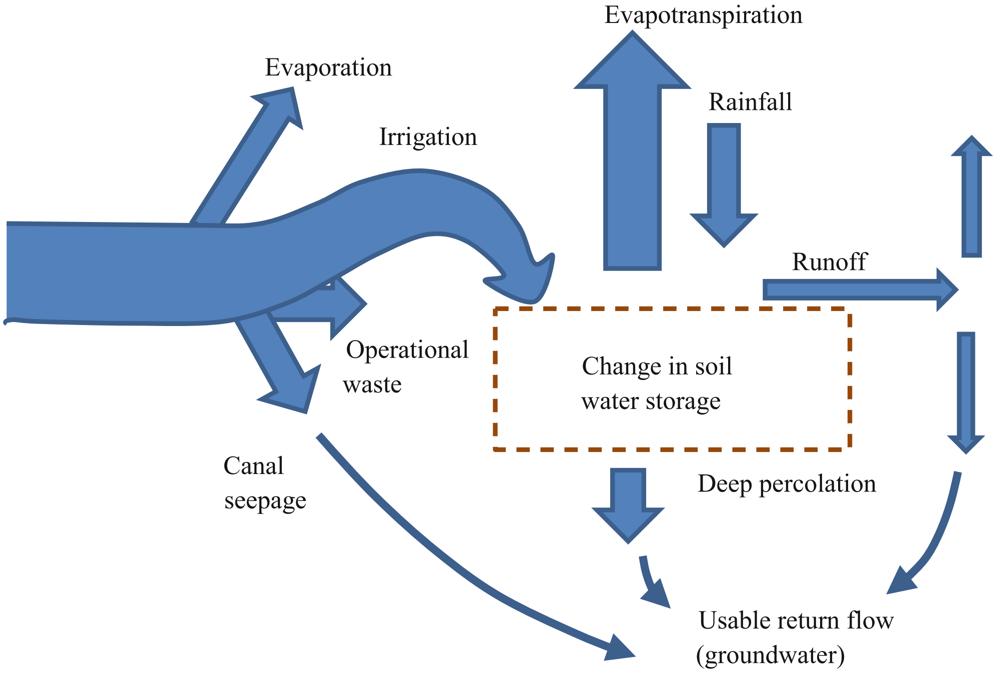

Fig. 1.16 Farm scale irrigation water balance (After NRCS – NEH)

however, the vertical processes in the soil profile are the focus of these chapters. Use of a model that tracks soil profile water and nutrient content enables better estimates of plant requirements, leading to lower nutrient waste and environmental contamination. Two of the important sources of nutrients are manure and wastewater. The first two chapters in this section describe wastewater pathogens and pollution and the application of waste to soils.

Contaminants and Waste Application to Soils (Chaps. 23 and 24)

Irrigation systems and soils are increasingly used as a method of waste disposal. Waste contains beneficial nutrients; however, there are also disease carrying pathogens. Chapter 23 provides a brief introduction to pathogens, disinfection, wastewater characteristics, and waste treatment. Chapter 24 focuses on waste and wastewater application. The primary focus in Chap. 24 is the utilization of nutrients in livestock waste for agriculture. Treatment steps include pond and wetlands treatment, and waste application to fields. Degradation rates, salinity, nutrient concentration, volatilization, percent solids, pond retention time, climate, and other factors must be considered in the calculation of the depth of wastewater that should be applied by irrigation systems.

The *WINDS* Model (Chaps. 25, 26, 27, 28 and 29)

The soil is the control volume in the *WINDS* model, but it is part of a larger system. The interactions of the larger system with the soil profile are shown in Fig. 1.16. Even after touching the field surface, irrigation and rainfall are partitioned between infiltration and runoff. Water that enters the soil may be lost to deep seepage; however, just because water and nutrients are lost to seepage or runoff, does not necessarily mean that they are lost from the farm or irrigation district. The next field may be able to utilize the runoff or the pumped water from the aquifer (Fig. 1.16).

Chapter 25 focuses on nitrogen processes and salinity fate in soils. The nitrogen processes include fertilization, mineralization, denitrification, and plant uptake.

Chapter 26 presents the tipping bucket approach to modeling water, salt, and nitrogen movement in soils during storms or irrigation events. In the tipping bucket model, a mass balance is set up for each soil layer, and water, salt, and nitrogen are routed to the next layer in the soil profile if there is water movement between layers. The foundation of the *WINDS* model is the mass balance: change in storage = input − output + reaction. The water balance begins with the partition between infiltration and runoff. In the WINDS model, the infiltration depth is either specified in a worksheet or it is calculated with the Green-Ampt equation or NRCS curve numbers, based on storm intensity and duration.

Chapter 27 introduces basic concepts associated with the conservation of energy equation. It then describes the relationships between soil energy (gravitational + matric), hydraulic conductivity, and water flux. Energy diagrams are used to show the relationship between matric potential energy, elevation energy, and total energy in soils. The Van Genuchten and Brooks-Corey relationships between matric potential, hydraulic conductivity, and water content are also described.

Chapter 28 combines the conservation of energy and conservation of mass equations in order to model water flux in response to energy gradients. The *WINDS* model is used to demonstrate the Richards equation and the van Genuchten soil parameters. The second part of the chapter focuses on modeling water content in the soil in the presence of a water table. Drainage algorithms calculate the fluctuation of the water table in the presence of periodic infiltration events and evapotranspiration. The *WINDS* drainage algorithm was derived by integrating the van Genuchten equation. Lower soil layers remain in hydraulic equilibrium with the water table and upper layers are disconnected from the water table. A decision algorithm determines which layers are in equilibrium with the water table.

Chapter 29 demonstrates the use of the *WINDS* model in agriculture. It describes the algorithms for crop growth, ET, irrigation, rainfall, water content, and leaching. The chapter focuses on two case studies, an irrigated cotton crop in an arid region, and rainfed agriculture in a tropical climate. The examples demonstrate the relationship between transpiration, evaporation, crop maturity and crop stress. They show how weather station data is used in the WINDS model. Algorithms for modeling partially wetted soils, crop stress, Green-Ampt infiltration, remote sensing and crop coefficients, evapotranspiration in the presence of water or salinity stress, salinity stress, and nitrogen stress are also presented.

Subsurface Drainage Systems (Chaps. 30 and 31)

Chapter 30 reviews engineering and environmental considerations in subsurface drainage design and installation. Engineering equations for drain diameter, particle size fractions in drain envelopes, and auger hole measurement of lateral soil horizontal conductivity are also presented. Chapter 31 focuses on hydraulic and hydrologic models of the water table in the presence of subsurface drains. The traditional drainage model is the Hooghoudt equation for steady-state calculation of water table elevation. The Bower and van Schilfgarde equation and the Bureau of Reclamation equations enable simulation of water table elevation over time. An example shows how to use engineering economic analysis in order to select drain spacing and elevation. Kirkham developed a two-dimensional solution of flow to parallel drains and then modified it for transient and spatial analysis of drained fields. Kirkham's method is implemented in the *WINDS* model, and the chapter concludes with a *WINDS* drainage simulation.

The Value of Water

In today's world, water is becoming scarce in some regions. Who is going to have access to the water, and what are they going to pay for it? Irrigation and drainage engineers will be at the center of some of these controversies. At the very least, engineers will provide the data and models that policy makers will use to answer these questions. As such, engineers should have some familiarity with the value of water and the ways that it can be distributed. One of the important concepts that has arisen in recent years is the concept of virtual water.

The value of water depends on supply, demand, and cost of water resources development. In water stressed regions, the value of water can be greater than the value of food produced by the water. In these regions, one strategy of "water resources development" that is gaining in popularity is the concept of virtual water. A community can import water in the form of food – virtual water. The virtual water concept postulates that if a region imports food, then it is actually importing the amount of water required to grow that food. For example, if water for wheat requires 1,000 m^3/metric ton to produce (Table 1.4), then importing a metric ton of wheat is the same as importing 1,000 m^3 of water.

The United States and Canada, with abundant rainfall in North America, are the largest exporters of water in the form of food commodities (Table 1.5). The largest virtual water

Table 1.4 Water volume for commodities

Wheat	1,000 m^3/metric ton
Citrus	1,000 m^3/metric ton
Rice	2,000 m^3/metric ton
Fresh beef	15,000 m^3/metric ton
Poultry	6,000 m^3/metric ton

Table 1.5 Virtual water exporters

Country	10^9 m^3/yr	Per capita – m^3/yr
USA	758	2,600
Canada	272	8,400
Thailand	233	3,600
Argentina	226	5,800
India	161	150
Australia	146	7,300
Viet Nam	90	1,000
France	88	1,500

importers are, in order from first to last: Sri Lanka, Japan, Netherlands, Korea, China, Indonesia, Spain, Egypt, Germany, and Italy.

Water, on a per volume basis, is much less valuable to agriculture then to municipalities. The value of water in agriculture compared to the municipal value can be compared by looking at the yearly volume required per person for drinking, household management, and food production per year.

1. Drinking water requirement is 1 m^3/person/year.
2. Domestic and municipal uses require 100 m^3/person/year.
3. Food production requires about 1,000 m^3/person/year.

Typically, a large proportion of the most easily developed water resources are allocated to agriculture. As cities grow, they require more water, and they either try to develop more expensive water resources or they buy the water that was originally allocated to agricultural entities.

Within a given region, the value of water can be determined in two ways. It can be established by the actual cost of water delivery (infrastructure and energy costs), or it can be established by the opportunity cost, which is the highest price that someone is willing to pay for the water. For example, if water costs $30/ha-cm to deliver, and a golf course is willing to pay $300/ha-cm for water, and a farmer is only willing to pay $3/ha-cm, then the opportunity cost of the water (value) is $300/ ha-cm, while the actual cost of the water is $30/ha-cm. However, the farmer may continue to receive water at $3/ha-cm because it is his/her legal right. Because of the demand for urban water, some regions have allowed farmers to sell their water to cities rather than continue to grow crops.

The question of whether to allocate water based on opportunity cost or to restrict water to agriculture is often a complex political decision that must consider national food security, maintenance of the rural community, water law, and other considerations. This question is beyond the control of the irrigation engineer. However, one thing is certain. As water resources are stretched between competing demands, the value of the water increases, and the value of efficient water management increases with it. Thus, the value of irrigation engineering increases with the value of water.

Questions

1. List the components of a farm water balance.
2. Describe the major four irrigation methods (NRCS description).
3. Describe the different types of irrigation efficiency
4. In general, pressurized irrigation systems are considered to be more efficient than surface irrigation systems. What are some factors that may decrease the irrigation efficiency of some sprinkler systems to below that of some surface irrigation systems?
5. How do irrigation systems fail?
6. Summarize the virtual water concept.
7. What increases the value of the irrigation engineering?

References

Altaweel M, Watanabe CE (2012) Assessing the resilience of irrigation agriculture: applying a social-ecological model for understanding the mitigation of salinization. J Archeol Sci 39:1160–1171

Natural Resource Conservation Service. Engineering Field Handbook (1997) Part 652 Irrigation Guide. Chapter 5 (652.0501) Methods and systems to apply irrigation water. http://www.scribd.com/doc/12851870/National-Irrigation-Guide

Solomon K (1988) Irrigation water systems and water application efficiencies. Center for Irrigation Technology, Irrigation Notes. California State University, Fresno. http://cwi.csufresno.edu/wateright/880104.asp