Chapter 5
Irrigation System Performance

5.1 Introduction

Management of irrigation systems should be based on the desired objectives or outcomes consistent with economic, energy, environmental, labor, water, and resource constraints. Goals can vary from maximizing profit, producing a contracted yield, optimizing water resource use, maintaining the quality of produce, or assuring an attractive landscape. Managers cannot achieve these goals without considering the performance of the irrigation system.

This chapter discusses the basic characteristics of various irrigation systems, defines terms that quantify performance, describes basic requirements all systems must provide, gives a range of attributes for systems, and discusses how water supply requirements are governed by ET and system characteristics. Detailed characteristics of specific systems are presented in later chapters. The key here is to understand the basic systems and their relative performance.

5.2 Types of Systems

There are three general types of irrigation systems: (1) ***sprinkler irrigation***; (2) ***surface irrigation***; and (3) ***microirrigation***, including drip, trickle, and spray. All have advantages and disadvantages in given situations.

5.2.1 Sprinkler Irrigation

Sprinkler irrigation systems are used for agricultural or horticultural production and for landscape or turf applications. The principles of operation are the same for all applications even though the management objectives may differ. Sprinkler systems can be divided into four basic types: single-sprinkler, solid-set, moved lateral, and moving lateral systems. Figure 5.1 illustrates two types of sprinkler systems.

Single-sprinkler systems are designed to irrigate an entire area with only one sprinkler that is moved periodically or automatically moves across the area. Examples range from the single lawn sprinkler that is placed throughout the yard, to automatically moving systems equipped with a big gun sprinkler that throws water hundreds of feet (traveler irrigation system). The performance of single sprinkler systems depends on placing the sprinkler at the proper location for the correct amount of time. A disadvantage is that the systems generally apply water beyond the irrigated area to ensure that the targeted land is adequately watered. However, a significant advantage is that the single sprinkler system is quite versatile and widely used for irregularly shaped land areas.

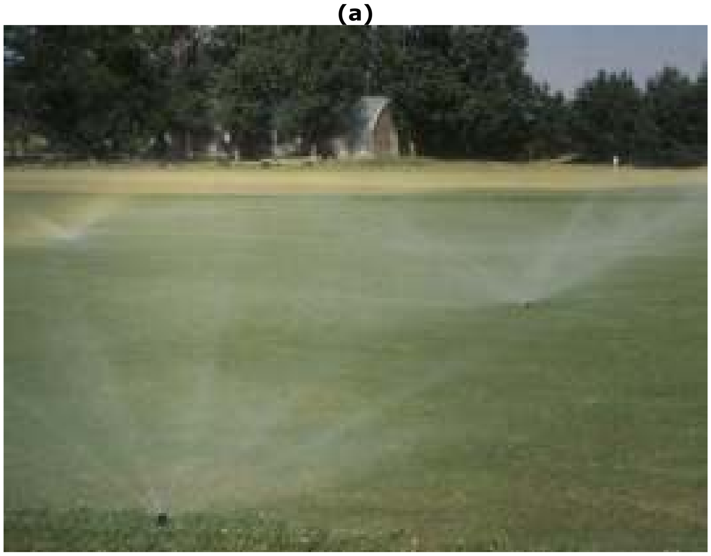
A step up in complexity from the single-sprinkler system is the system with multiple sprinklers placed along a pipe called a lateral. The basic components of lateral-based sprinkler systems are the mainline and one or more laterals. The mainline is a pipe network designed to carry

Dean E. Eisenhauer, Derrel L. Martin, Derek M. Heeren, & Glenn J. Hoffman. 2021. ASABE.

water from the water source to the laterals. The sprinkler devices are located on the lateral pipelines. Most lateral-based systems consist of multiple laterals. When the laterals are placed permanently in one location in the field, the system is called a ***solid-set*** system. Generally, the laterals and mainline of solid-set systems are installed under the soil surface and the sprinklers are mounted above ground with pipes called risers or the sprinklers are specially designed to pop up above the soil when water pressure builds in the lateral. Solid-set systems are commonly used on lawns, landscapes, golf courses, and some agricultural and horticultural applications. This type of system can be very efficient since each sprinkler in the system is only used in the area it was designed to irrigate. The systems are easily automated and can apply any depth desired.

To reduce investment costs, a single lateral could be set to water a portion of an irrigated area and then moved to multiple locations. The earliest and simplest of these ***moved lateral*** systems is carried by hand and is called a hand move system. The lateral can also be moved by pulling the lateral across the field. This type is called a tow line or towed sprinkler system. Laterals can be mounted on wheels that suspend the pipeline above the crop. These systems are called side roll systems because the wheels are rolled across the field to reposition the lateral. Because of the labor requirement, the moved laterals are usually left in one location for 8, 12, or even 24 hr. Thus, the systems usually apply large depths of water each irrigation.

(a)



(b)

Figure 5.1. (a) Center pivot sprinkler system used for agriculture, and (b) underground sprinkler system in turfgrass.

Automated systems have been developed to move the lateral across the field. Examples of ***moving lateral*** systems include center pivots and linear or lateral move systems. All of these systems use one lateral to irrigate a large area, but since the lateral moves at a controlled speed, the depth of water applied can be varied over a wide range.

5.2.2 Surface Irrigation

Several types of surface irrigation, including ***basins***, ***borders***, and ***furrows*** (Figure 5.2), are used depending on topography, soil texture, and the types of crops grown. Surface irrigation systems are used on agricultural or orchard crops and landscapes that have moderate slopes. With surface irrigation the water is distributed across the field as it flows over the soil surface. Surface irrigation methods generally have lower pressure requirements than sprinkler irrigation, and therefore are less expensive to operate per unit of water applied. The installation costs of surface systems may be lower than for sprinklers if land leveling is not necessary.

Three common problems occur with surface irrigation. To irrigate uniformly, water must advance across the field quickly. This means that some water will run off of the field. Some states have regulations that prohibit irrigation water from running off the field. The runoff problem is largely overcome if a runoff recovery system or ***return flow system*** is a component of the surface system. The second problem is that surface irrigation is labor-intensive. Irrigators are generally unwilling or unable to invest the time needed to irrigate efficiently. This results in excessive applications leading to water losses in the form of runoff or deep percolation. Deep percolation resulting from nonuniform distribution of infiltration is a third common problem with surface irrigation.

A surface irrigation system consists of some type of water supply mechanism, similar to a mainline for sprinkler systems. This supply mechanism may be a "head" ditch, gated pipe, or buried pipelines with valves at the surface. A variation is the use of siphon tubes to deliver water from a supply ditch.

Whatever water supply device is used, water will flow across a constrained portion of the field. This area of the field may be constrained by small dikes in a border irrigated field or furrows in furrow irrigation. Sometimes an area is leveled and surrounded by small dikes. This type of system is called basin irrigation. If the field is nearly level in both the direction of flow and the transverse direction, the water that would run off the field may be blocked and forced to stay on the field.

Figure 5.2. Furrow irrigation with gated pipe; one type of surface irrigation. (Photo courtesy of Steve Melvin.)

5.2.3 Microirrigation

Microirrigation systems consist of laterals containing emitters (***drip irrigation***) or ***microsprinklers***, or laterals with outflow continuously along their lengths (soaker hose). Drip irrigation on the soil surface, also known as ***trickle irrigation***, is illustrated in Figure 5.3. Microirrigation is unique in that the discharge devices are intended to irrigate individual or groups of plants and not the entire soil surface. In landscape applications the flow rate from each emitter may be quite small, while in orchard applications several devices may be required to apply the needed irrigation. Microsystems are usually permanently installed and can be expensive. Labor requirements are minimal although maintenance may be high for situations where the water requires filtration.

Microirrigation systems are popular on high-value crops in locations where water is expensive, in short supply, or of degraded quality. Emitters and microsprinklers have very small orifices or outlets. Since the orifices are small, it is necessary to prevent plugging by soil particles or microorganisms such as bacteria.

Microsystems are among the most expensive methods of irrigation, primarily because of the expensive piping system and filtration requirements. They are generally not applicable to row crop production due to the expense and the need to remove the system each season. The latter problem is overcome by burying the laterals beneath the tillage zone, a practice called ***subsurface drip irrigation***

Figure 5.3. Surface drip irrigation system in India. (Photo credit: IDE India.)

(SDI). Microirrigation is used extensively for landscape applications, especially for trees, shrubs, and gardens. Advantages of these systems include: (1) high efficiency, because evaporation loss is small since the whole plant area is not wetted; (2) water is applied at very low rates so runoff is negligible even for steep slopes; and (3) systems are easily automated to minimize labor.

5.3 Performance Measures

Achieving management objectives requires that water be applied at the proper time, rate and quantity, and in the desired location. However, irrigation systems are not perfect which results in some areas receiving more water than others while some water is simply lost to evaporation. How should an irrigator respond to inefficiency and nonuniformity? How does a management change affect operation and performance? To address these questions, relationships have been developed to quantify performance.

5.3.1 Efficiency

Irrigation systems are never 100% efficient. The major ways water can be "lost" from an irrigated field are illustrated in Figure 5.4. Water is never truly lost, but not all applied water is beneficially used. For irrigation systems such as sprinklers that throw water into the air while irrigating, some ***evaporation*** occurs while the droplets are in the air or once they reach the crop or soil surface. Research suggests that there is little evaporation of the drop while in the air. Losses to evaporation are usually significantly less than 10% of the applied water. If wind blows, droplets may be blown outside of the land to be irrigated. This is called drift. Drift losses may be important and are often significantly higher than evaporation losses.

When water is applied at a rate that exceeds the infiltration rate of the soil, water begins to accumulate on the soil surface. If the water builds up sufficiently it will begin to run off the soil surface where applied or off of the field. The ***runoff*** water could also infiltrate at a lower elevation in the field leading to poor uniformity of infiltration. When water is applied to the field, in excess of the soil water depletion (SWD), the excess water may percolate past the root zone, a quantity called ***deep percolation***. Irrigation water that remains in the soil at the end of the growing season may also be lost if off-season rains would have replenished the root zone anyway. Thus, there are many ways applied water can be lost from the plant root zone. The manager must minimize losses where possible, yet invariably some losses will occur. In this case, the manager should know how much water might typically be lost so that applications can be adjusted to meet plant needs. ***Application efficiency*** (E_a) is usually defined as the fraction of the applied water that is stored in the root zone and is available for crop water use. The water stored in the root zone is often called ***net irrigation*** and the total

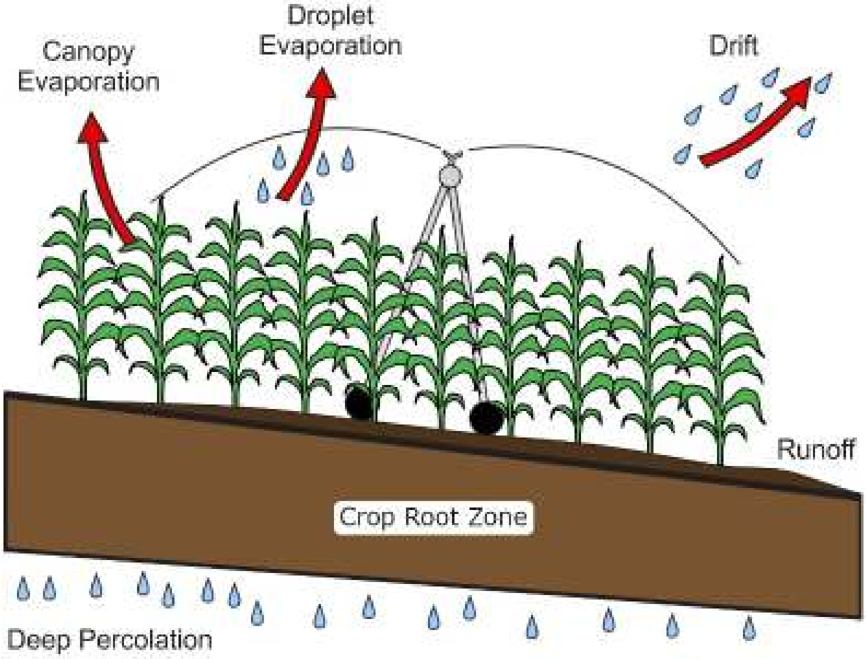


Figure 5.4. Illustration of how water is "lost" from an irrigation system.

amount applied to the field is termed ***gross irrigation***. Thus, the application efficiency is defined as:

$$E_a = 100\%\left(\frac{d_n}{d_a}\right) \tag{5.1}$$

where: E_a = application efficiency,
d_n = net irrigation depth, and
d_a = gross or applied irrigation depth.

The E_a can be expressed as either a decimal fraction (i.e., ranging from 0 to 1.0) or a percentage (ranging from 0 to 100%). The applied depth refers to the volume applied from the water source divided by the area irrigated by that water. The E_a is the result of system characteristics, management, soil and crop conditions, and the weather--especially rainfall. Therefore, there is a broad range of application efficiencies.

This chapter focuses on irrigation water use in terms of the performance of the irrigation system (e.g., application efficiency, application uniformity). Water use can also be evaluated in terms of the yield of the irrigated crop, with the idea of increasing the ratio of crop production to water use. This has been called water use efficiency (Irmak et al., 2011) or water productivity (Trout and DeJonge, 2017; Giordano et al., 2017). In general, advancements in irrigation technology can improve both application efficiency and water productivity (Evett et al., 2020).

5.3.2 Application Uniformity

Irrigation systems are not capable of applying exactly the same depth of water to every location in the field. The distribution of applied water varies because of factors such as wind drift, improper pipeline pressure, poor design, and inappropriate system management. For many irrigation systems, the depth of water applied at a point is nearly the same as the depth entering the soil (infiltration) at the point. Thus, nonuniform applications lead to nonuniform depths of infiltration and ultimately to varying amounts of soil water in the root zone. This nonuniformity adversely affects plant performance so information about the uniformity of application is needed to manage irrigation systems effectively. Illustrations of the effects of poor water distribution on plant health are shown in Figure 5.5. The center pivot pictures (Figures 5.5a and 5.5b) are in Nebraska soybean fields during a drought year (August 2012), which exacerbated the effect of poor uniformity. Further, nonuniform application leads to more deep percolation which results in lower application efficiencies and sometimes to chemical leaching.

Uniformity can be measured for all irrigation systems. For sprinkler systems collection containers (catch cans) or rain gauges are placed in a grid pattern in the field. The irrigation system is then operated for a period of time and the depth of water caught in each container is measured. For microirrigation systems, the volume of water emitted in a given time is measured for all emitters on a lateral. For surface irrigation, experiments can be conducted to determine the depth of water that infiltrates at various points within the field.

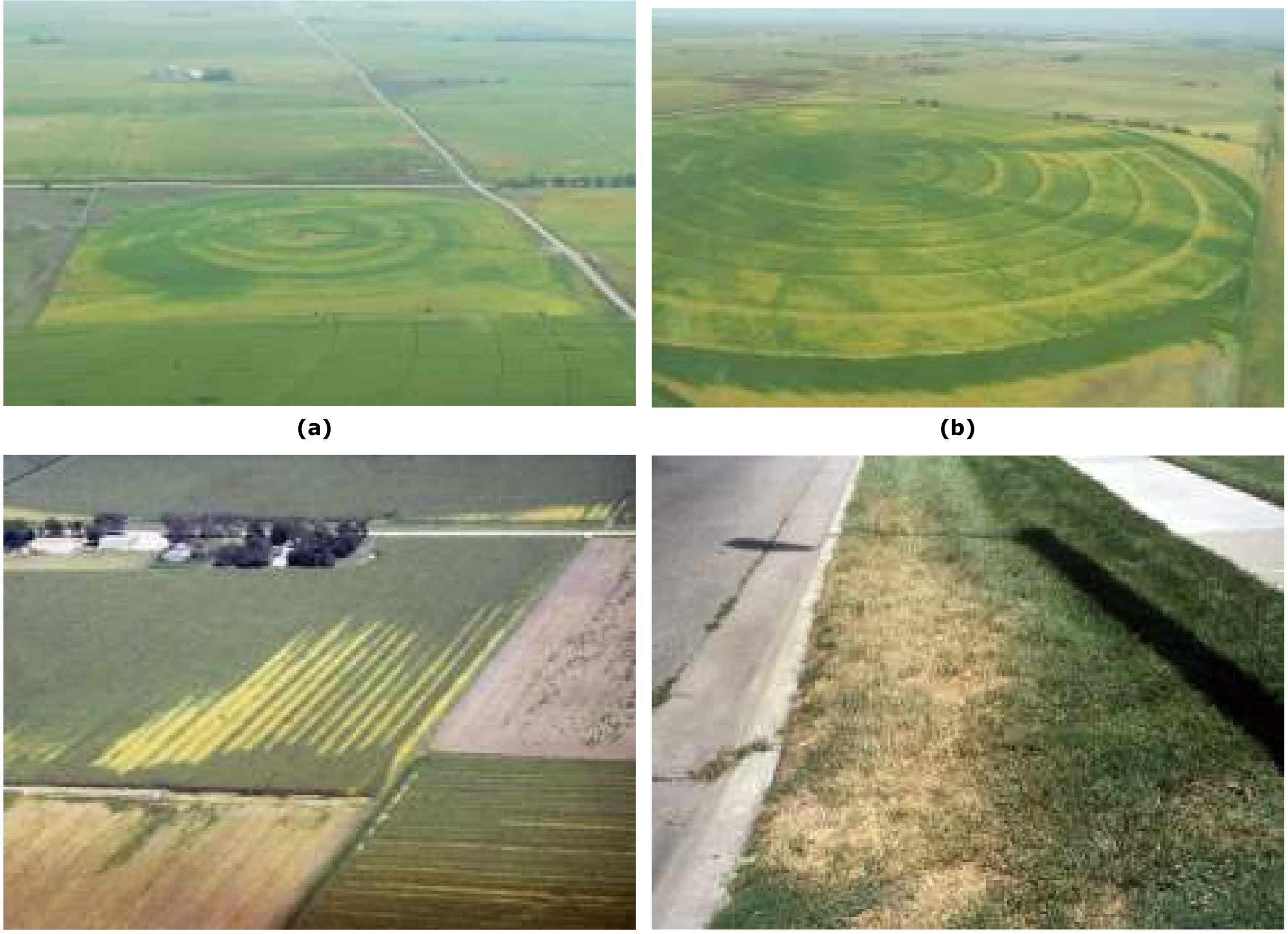
To evaluate uniformity, a method is needed to compute a performance value from field test data. The two most commonly used methods are the ***distribution uniformity*** (DU) and the Christiansen uniformity coefficient.

The DU is a relatively simple method where:

$$DU = \frac{d_{LQ}}{d_z} \tag{5.2}$$

where: d_{LQ} = average low-quarter depth of water infiltrated, and
d_z = mean depth infiltrated for all observations.

The value of d_{LQ} is the average depth of application for the lowest one-quarter of all measured values when each value represents an equal area of the field. You can determine the low-quarter depth by ranking observed depths and computing the average for the smallest 25% of the values. Since DU is a ratio with the value of the denominator always being larger than the numerator,



(a) (b)

(c) (d)

Figure 5.5. Irrigation system having poor water distribution: (a) center pivot irrigation system with large leaks (photo courtesy of Gary Zoubek), (b) center pivot with end gun providing a larger application depth than the rest of the system (photo courtesy of Gary Zoubek), (c) furrow irrigation, and (d) underground sprinkler system for turfgrass.

DU is always between 0 and 1. The larger the value of DU, the better the uniformity.

The ***Christiansen uniformity coefficient*** (CU) is another index to indicate application uniformity. When each observation represents the same area, the CU is determined as:

$$CU = 100\% \left(1 - \sum_{i=1}^{n} \frac{\left| d_i - d_z \right|}{n\, d_z} \right) \qquad (5.3)$$

where: d_i = depth of observation i,

d_z = mean depth infiltrated for all observations, and

n = number of observations.

The calculated value is multiplied by 100 to provide an index value between 0 and 100. Note that $\sum_{i=1}^{n} \frac{\left| d_i - d_z \right|}{n}$ is the average deviation from the mean. Thus, another way to write Equation 5.3 is: 100% (1 – average deviation ÷ mean depth infiltrated).

Equation 5.3 was developed to interpret data collected with catch cans placed under sprinkler irrigation system. Typically, water depths in the equation are amounts caught in the cans, not infiltrated water. Since the distribution of infiltration is really what is of interest, the depth of water caught in the can used in Equation 5.3 will indicate infiltrated water only if no surface runoff occurs.

Example 5.1

Given: A sprinkler system was evaluated using 20 catch can containers. The depth caught in each container is given below.

#	d_i (in)	#	d_i (in)	#	d_i (in)	#	d_i (in)
1	1.2	6	1.7	11	2.1	16	2.0
2	2.6	7	2.9	12	1.7	17	1.6
3	1.8	8	2.7	13	1.9	18	2.3
4	2.1	9	1.6	14	1.4	19	1.8
5	2.2	10	2.0	15	2.4	20	2.0

Find: Compute the distribution uniformity (DU) and Christiansen's uniformity coefficient (CU).

Solution: Rank the data in descending order, compute d_z, and then calculate d_{LQ}.

#	d_i (in)	$\lvert d_i - d_z \rvert$	#	d_i (in)	$\lvert d_i - d_z \rvert$	#	d_i (in)	$\lvert d_i - d_z \rvert$	#	d_i (in)	$\lvert d_i - d_z \rvert$
1	2.9	0.9	6	2.2	0.2	11	2.0	0.0	16	1.7	0.3
2	2.7	0.7	7	2.1	0.1	12	1.9	0.1	17	1.6	0.4
3	2.6	0.6	8	2.1	0.1	13	1.8	0.2	18	1.6	0.4
4	2.4	0.4	9	2.0	0.0	14	1.8	0.2	19	1.4	0.6
5	2.3	0.3	10	2.0	0.0	15	1.7	0.3	20	1.2	0.8

d_{LQ} = average of #16 to 20 = 1.5 in

d_z = average of #1 to 20 = 2.0 in

Then compute the individual deviations $\lvert d_i - d_z \rvert$ and the sum of deviations $\sum \lvert d_i - d_z \rvert = 6.6$

Then: $$DU = \frac{d_{LQ}}{d_z} \qquad DU = \frac{1.5}{2.0} = 0.75 \qquad \text{(Eq. 5.2)}$$

$$CU = 100\% \left(1 - \sum_{i=1}^{n} \frac{\lvert d_i - d_z \rvert}{n\, d_z} \right) \qquad \text{(Eq. 5.3)}$$

$$CU = 100\% \left(1 - \frac{6.6}{20 \times 2.0} \right) = 84\%$$

Typically, CU values are used for sprinkler and microirrigation systems while DU has become more popular for surface systems. However, some organizations use DU exclusively for all irrigation systems.

Methods used to measure the uniformity of center pivot irrigation systems are unique and a modified CU is normally used. The uniformity of a center pivot is measured by placing containers along two radial lines. The cans are usually placed with uniform spacing from 5 to 15 ft apart along each line. Then the pivot is operated so that the lateral passes over the containers. Since the pivot operates in a circular fashion, a container located far from the pivot point represents more area than one close to the pivot point. Therefore, the Heermann and Hein coefficient of uniformity (CU_H) is ordinarily used for pivots (Heermann and Hein, 1968):

$$CU_H = 100\% \left(1 - \frac{\sum_{i=1}^{n} \lvert d_i - d_z^* \rvert \, S_i}{\sum_{i=1}^{n} d_i \, S_i} \right) \qquad (5.4)$$

where: S_i = distance from the pivot point to the container, and
d_z^* = weighted mean infiltration, which is equal to:

$$d_z^* = \frac{\sum_{i=1}^{n} d_i S_i}{\sum_{i=1}^{n} S_i} \tag{5.5}$$

Uniformity values are not used like efficiency terms; rather they provide an index of performance. The optimal value of CU or DU depends on the price of irrigation water, the value of the irrigated crop, the costs of drainage or water quality impacts on the environment, and the cost of system renovation and/or management changes. Guidelines to judge whether uniformity is acceptable have been established. For moved lateral sprinkler systems, a CU of 80 (or DU of 0.7) is commonly the lowest acceptable uniformity. For center pivots, a $CU_H = 90$ is often achieved. For furrow systems, a DU of 0.6 is frequently the lowest acceptable value. The DU for microirrigation systems (also known as emission uniformity) should be at least 0.8.

5.3.3 Adequacy of Irrigation

How should an irrigator react to nonuniformity? If the d_z equals the average SWD for each irrigation, then about half of the field will receive more water than needed to refill the crop root zone and deep percolation will ultimately occur. The other half of the field will not receive enough water to refill the root zone and plant water stress may occur. The irrigation manager is continually faced with this tradeoff between excessive deep percolation and plant water stress. The management decision affects profits and E_a. In this context, an important variable is the adequacy of irrigation.

Adequacy of irrigation is the percent of the field that receives the desired depth, or more, of water. It can most easily be evaluated by plotting a frequency distribution of infiltration depth as shown in Figure 5.6. Figure 5.6 is based on the data in Example 5.1 and assumes that each data point represents 5% of the field area. The curve is developed by grouping field measurements of infiltration depth in descending order and computing the percent of the field area that receives at least a given depth of water. The point where the curve intersects the desired depth indicates the percent of the field that is being adequately irrigated. In example 5.1, 5% of the area receives 2.9 in or more while 100% of the area receives 1.2 in or more. Assuming a desired depth of infiltration of 1.6 in, from Figure 5.6 we find that 90% of the land received the desired depth of infiltration or more. Thus, 90% of the area is adequately irrigated. The remaining 10% of the field experienced some plant water stress. Well designed and managed irrigation systems should adequately irrigate at least 80 to 90% of the field. The appropriate adequacy of irrigation depends on many factors and probably varies during the growing season. With an existing irrigation system, the manager can vary the average depth of application to change the adequacy. This amounts to a proportional change to the distribution curve in Figure 5.6, with the distribution curve retaining the original shape. To change the shape of the distribution curve for sprinkler and microirrigation systems may require system modification, which is usually impractical during the season. With

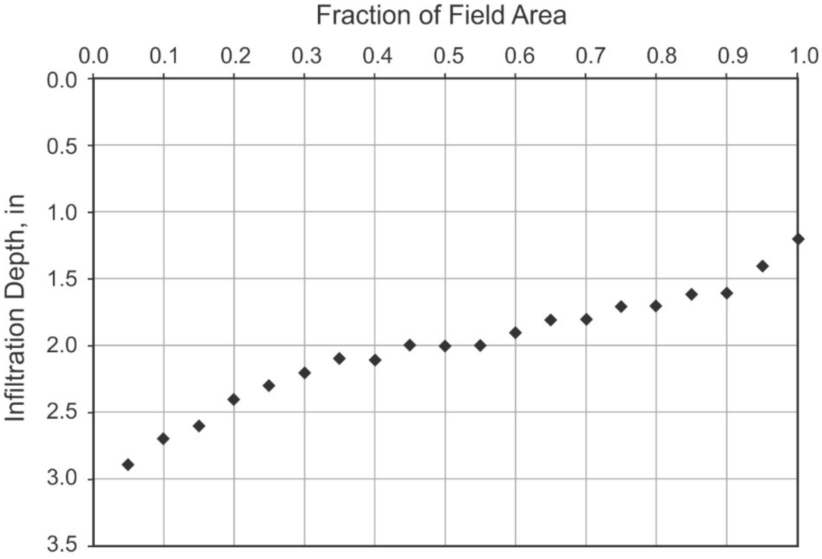


Figure 5.6. Distribution of infiltration based on data from Example 5.1.

surface irrigation, the shape of the distribution curve can be changed through system management as will be discussed in Chapter 10. Of course, if an irrigator increases the average depth applied, more deep percolation will occur. There is a direct link between E_a and uniformity.

5.3.4 Application Efficiency of the Low Quarter: Unification of Efficiency and Uniformity

It is important that all water "losses" during application be considered in an efficiency calculation. These losses shown in Figure 5.4 include:

- evaporation and drift,
- runoff,
- deep percolation due to nonuniform infiltration, and
- deep percolation due to excessive application.

Deep percolation occurs whenever infiltration exceeds the SWD. Excess infiltration can be caused by both the nonuniformity of application and excessive application. Non-uniformity of application is usually a result of a problem with the system for sprinkler and microirrigation, while excessive application is a result of system management. With surface irrigation, non-uniformity of application can also be a result of system management, e.g., if the flow rate in furrows is too low. Percolation caused by the nonuniformity occurs because the manager must decide how much of the field should be adequately irrigated. A common, albeit somewhat arbitrary, approach is to use the average low-quarter depth as the "management depth." Managing according to the average low-quarter depth results in approximately 90% of the field being adequately irrigated and potentially about 10% of the field being under irrigated.

Conservation of mass requires that the following water balance equation holds when conveyance losses (discussed later) are ignored:

$$d_g = d_z + d_r + d_{ev} \tag{5.6}$$

where: d_g = gross depth applied,
d_z = average depth infiltrated,
d_r = depth of runoff, and
d_{ev} = depth of evaporation and drift.

Rearranging Equation 5.6 results in:

$$d_z = d_g - d_r - d_{ev} \tag{5.7}$$

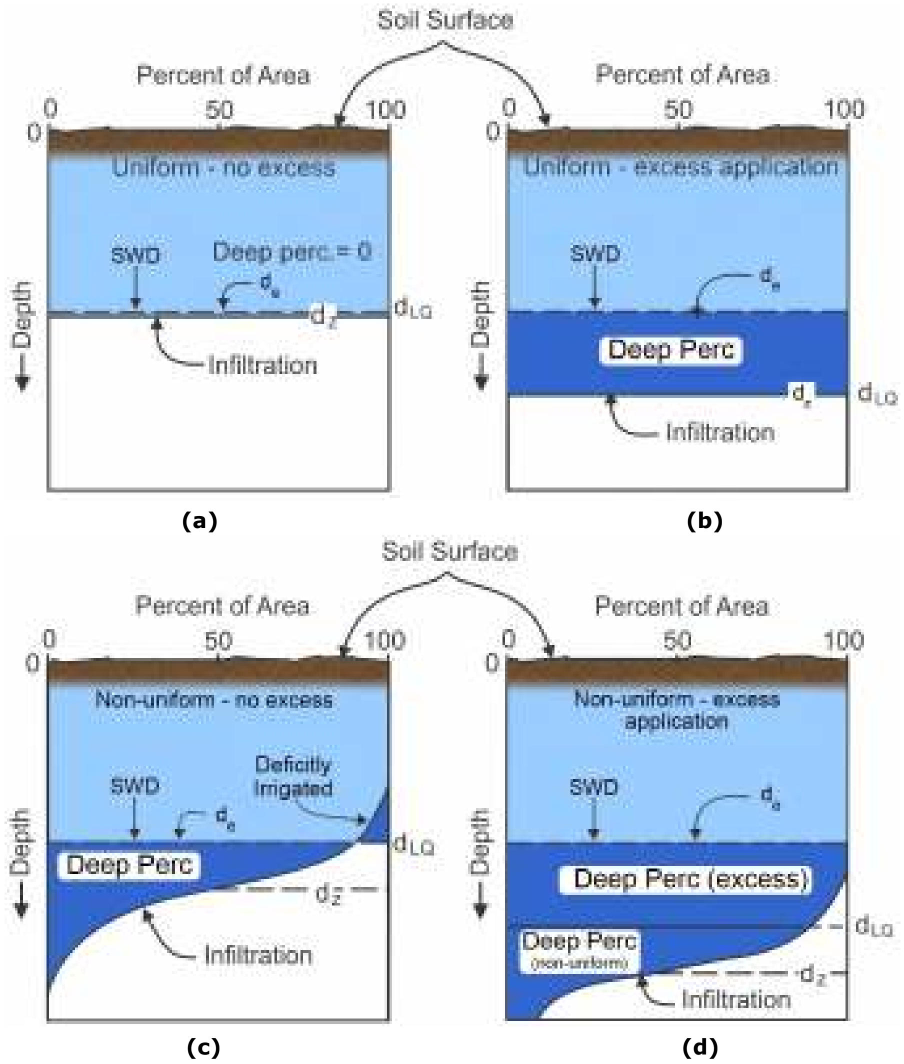
Note that Equation 5.7 accounts for above-ground losses, but the d_z includes both water that will be stored in the root zone and deep percolation. Rearranging Equation 5.2 yields:

$$d_{LQ} = (DU)(d_z) \tag{5.8}$$

The effectiveness of d_{LQ} depends upon the quantity of infiltration relative to the SWD. The ***effective depth*** (d_e) is the irrigation water that remains in the root zone for plant use, accounting for SWD and assuming that any irrigation depth in excess of the d_{LQ} will be lost to deep percolation (i.e., assuming a 90% adequacy of irrigation). The d_e, a managed term, is the amount of water that will be used in irrigation scheduling; its utility will be illustrated in Chapter 6. Figure 5.7 illustrates the concept of d_e with four scenarios. In 5.7a, the infiltrated water is perfectly uniform (DU = 1.0) and equal to SWD. No deep percolation would occur in this scenario. In this case, $d_{LQ} = d_z = d_e$.

In Figure 5.7b, the infiltrated water is perfectly uniform, but, due to excessive application, infiltration exceeds SWD. In this case, $d_{LQ} = d_z$ and $d_e = SWD$. The excessive application can be caused by irrigating too frequently or operating the system too long for the existing SWD. The interval between irrigations can be increased as long as SWD does not exceed the ***allowable depletion*** (AD)–a concept discussed in Chapter 6.

Nonuniform infiltration is illustrated in 5.7c. Here, the $d_{LQ} = SWD = d_e$. In this case, deep percolation is not due to excessive application caused by applying too much water or applying water too frequently but is due to the nonuniformity of the infiltration. The majority of the



(a) (b)

(c) (d)

Figure 5.7. Distribution of infiltrated irrigation water and deep percolation under four scenarios.

field (approximately 90%) experiences deep percolation because of the management decision to only allow about 10% of the field to be under irrigated.

Figure 5.7d illustrates the case where there are deep percolation losses due to both excess application and nonuniform infiltration. The figure illustrates the division of the two losses. In this case, $d_e = SWD$.

Figure 5.7 can be summarized by the following equations:

$$\text{If } d_{LQ} \le SWD, \text{ then } d_e = d_{LQ} \quad (5.9)$$

$$\text{If } d_{LQ} > SWD, \text{ then } d_e = SWD \quad (5.10)$$

Finally, the concepts of uniformity (irrigation adequacy), d_{LQ}, and d_e can be incorporated into the definition of application efficiency. The ***application efficiency of the low-quarter*** (E_{LQ}), discussed by Burt et al. (1997), is defined as:

$$E_{LQ} = 100\% \left(\frac{d_e}{d_a} \right) \quad (5.11)$$

where: E_{LQ} = application efficiency of the low-quarter (%), and
d_a = depth applied from the original source.

Determination of the depth of water from the original source is straightforward except when runoff recovery is part of the system. Either Equation 3.1 or 3.3 can be used for the calculation of d_a. Without runoff recovery, d_a and d_g are equal; d_a is always equal to the volume of water taken from the original source, such as a well, divided by the total land area irrigated. Runoff recovery, discussed in detail in Chapter 10, is a common practice in surface irrigation. If conveyance losses are ignored, the relationship between d_a and d_g for a closed runoff recovery system (runoff water reapplied on the same field) is:

$$d_a = d_g - d_r R_t$$

$$d_a = d_g (1 - R_r R_t) \tag{5.12a}$$

while, for an open runoff recovery system (runoff water reapplied on different field):

$$d_a = \frac{d_g}{1 + R_r R_t} \tag{5.12b}$$

where: d_g = gross depth applied which includes the volume applied from the runoff recovery system,
d_r = depth of runoff,
R_r = runoff ratio (d_r / d_g), and
R_t = return ratio, the depth of water returned (reused) divided by the depth of runoff.

Example 5.2

In Example 5.1, the DU was 0.75 and d_z equaled 2.0 in. If d_a = 2.2 in, runoff is zero, and SWD = 1.6 in, determine the system's E_{LQ} and d_{ev}.

Given: d_z = 2.0 in
d_a = 2.2 in
d_r = 0
SWD = 1.6 in
DU = 0.75

Find: d_{ev}
E_{LQ}

Solution:

Rearranging Equation 5.6

$$d_{ev} = d_g - d_z - d_r \quad \text{(Eq. 5.6)}$$

$$d_{ev} = 22 \text{ in} - 20 \text{ in} - 0 = 0.2 \text{ in}$$

Using Equations 5.8, 5.9, and 5.11, you will find that

$$d_{LQ} = (DU)(d_z) \quad \text{(Eq. 5.8)}$$

$$d_{LQ} = (0.75)(2.0 \text{ in}) = 1.5 \text{ in}$$

Since d_{LQ} < SWD, d_e = 1.5 in, according to the criteria in Equation 5.9.

Since d_r = 0, d_a = d_g = 2.2 in

$$E_{LQ} = \left(\frac{d_e}{d_a}\right) \times 100\% \quad \text{(Equation 5.11)}$$

Thus, $E_{LQ} = \left(\frac{1.5 \text{ in}}{2.2 \text{ in}}\right) \times 100\% = 68\%$

Example 5.3

Repeat Example 5.2 if SWD equaled 1.2 in.

Solution:

Now, d_{LQ} > SWD, thus, Equation 5.10 applies and d_e = SWD = 1.2 in

Thus, E_{LQ} = (1.2 in)/(2.2 in) × 100% = 55%

5.3.5 The Scheduling Coefficient

Another term that is an index of irrigation uniformity and efficiency is the scheduling coefficient (Solomon, 1988). It is commonly used for a description of turf sprinkler systems. It is used to calculate how long a system needs to apply water with the realization that the water application will not be perfectly uniform. For example, if the goal is to apply 0.5 in of water and the sprinkler system applies 0.25 in/hr, it would take 2 h to apply the desired depth *if the water were distributed uniformly across the irrigated area*. However, it usually is not! Thus, to adequately irrigate the desired proportion of the lawn, the sprinkler must be run longer than 2 hr.

Assuming that 90% adequacy is the goal, the ***scheduling coefficient*** (SC) is calculated as:

$$SC = \frac{d_z}{d_{LQ}} \tag{5.13}$$

As you can see, SC is simply the inverse of DU. The SC indicates how much longer an irrigation system will need to run in order to account for non-uniformity.

Example 5.4

A sod farm sprinkler system was tested and shown to have a DU of 0.80. If the average depth caught in the cans (d_z) was 1.5 in and the sprinkler had been running for 5 h, determine the scheduling coefficient (SC), the d_{LQ}, and the number of hours the sprinkler would need to run to achieve the same result if the pattern had been perfectly uniform.

Find: d_{LQ} and SC
Time if uniformity had been perfect

Solution:

$$d_{LQ} = (DU)(d_z) \qquad \text{(Eq. 5.8)}$$

$$d_{LQ} = (0.8)\,(1.5\text{ in}) = 1.2\text{ in}$$

$$SC = \frac{d_z}{d_{LQ}} \qquad \text{(Eq. 5.13)}$$

$$SC = \frac{1.5}{1.2} = 1.25$$

An SC of 1.25 indicates that the sprinkler had to run 25% longer because of uneven distribution. Thus, with perfect uniformity, the time to operate would have been:

Time = 5 h / 1.25 = 4 h

5.3.6 Chemical Leaching Losses

Deep percolation losses not only decrease irrigation efficiency, but also result in chemical movement or loss below the root zone. The volume of deep percolating water due to nonuniformity can be designated V_{dp1}. For an adequacy of 90% and a normally distributed (in a statistical sense) water application depth, the V_{dp1} is given by:

$$V_{dp1} = V_z\,(1 - F_1) \tag{5.14}$$

where: $V_z = d_z A$ = volume of water infiltrated,
d_z = average depth of water infiltrated,
A = total irrigated area, and
F_1 = factor (Table 5.1).

Table 5.1. Relationship between CU and F1 for a 90% adequacy of irrigation.

CU	F1	CU	F1
70	0.46	83	0.69
71	0.48	84	0.71
72	0.49	85	0.73
73	0.51	86	0.75
74	0.53	87	0.77
75	0.55	88	0.78
76	0.57	89	0.80
77	0.58	90	0.82
78	0.60	92	0.86
79	0.62	94	0.89
80	0.64	96	0.93
81	0.66	98	0.96
82	0.67		

Deep percolation due to excessive average irrigation depths and/or irrigating too frequently (excessive application) is denoted V_{dp2} and:

$$\text{If } d_{LQ} \le SWD,\text{ then } V_{dp2} = 0$$

$$\text{If } d_{LQ} > SWD,\text{ then } V_{dp2} \approx 0.95\,A\left(d_{LQ} - SWD\right) \tag{5.15}$$

Total deep percolation, V_{dp}, is given by:

$$V_{dp} = V_{dp1} + V_{dp2} \tag{5.16}$$

The depth of deep percolation, d_p, is:

$$d_p = \frac{V_{dp}}{A} \tag{5.17}$$

The amount of chemical lost with the leachate can be calculated by:

$$C_l = 0.226\ C\ d_p \qquad (5.18)$$

where: C_l = chemical loss (lb/ac),
C = concentration of the chemical in the leachate (deep percolation) (ppm), and
d_p = depth of deep percolation (in).

Example 5.5

Find the nitrate leached (lb/ac) for the field illustrated in Example 5.1 if the average concentration of nitrate-nitrogen in leachate is 20 ppm and SWD = 1.2 in.

Find: Determine the amount of nitrate-nitrogen leached from the field during each irrigation.

Solution:

Since we need to calculate this in lb/ac, assume that A = 1 ac.

From Table 5.1, F_1 = 0.71 for a CU of 84%.

Using Equations 5.14, 5.15, 5.16, 5.17, and 5.18:

$$V_{dp1} = d_z\ A\ (1 - F_1) \qquad \text{(Eq. 5.14)}$$

$$V_{dp1} = (2.0\ \text{in})\ (1\ \text{ac})\ (1 - 0.71)$$

$$V_{dp1} = 0.58\ \text{ac-in}$$

$$V_{dp2} = 0.95\ A\ (d_{LQ} - SWD) \qquad \text{(Eq. 5.15)}$$

$$V_{dp2} = (0.95)\ (1\ \text{ac})\ (1.5\ \text{in} - 1.2\ \text{in})$$

$$V_{dp2} = 0.29\ \text{ac-in}$$

$$V_{dp} = V_{dp1} + V_{dp2} \qquad \text{(Eq. 5.16)}$$

$$V_{dp} = 0.58\ \text{ac-in} + 0.29\ \text{ac-in} = 0.87\ \text{ac-in}$$

$$d_p = \frac{V_{dp}}{A} \qquad \text{(Eq. 5.17)}$$

$$d_p = \frac{0.87\ \text{ac-in}}{1\ \text{ac}} = 0.87\ \text{in}$$

$$C_l = 0.226\ C\ d_p \qquad \text{(Eq. 5.18)}$$

$$C_l = 0.226\ (20)\ (0.87) = 3.9\ \text{lb/ac}$$

Thus, 3.9 lb/ac of nitrate-nitrogen are lost to leaching for each irrigation.

Another approach for finding the average d_p, if data from a uniformity test is available, is to determine the d_p at each irrigation catch can and then averaging. From Example 5.1, the d_p in Can No. 1 is 0 in (1.2 in caught – 1.2 in SWD). For Can No. 20, it is 0.8 in (2.0 – 1.2). For the 20 cans in Example 5.1, the d_p is:

Can No.	Deep Perc. (d_p) (in)	Can No.	Deep Perc. (d_p) (in)
1	0.0	11	0.9
2	1.4	12	0.5
3	0.6	13	0.7
4	0.9	14	1.2
5	1.0	15	1.2
6	0.5	16	0.8
7	1.7	17	0.4
8	1.5	18	1.1
9	0.4	19	0.6
10	0.8	20	0.8

Averaging the 20 depths, we get an average d_p of 0.85 in, which compares well with the 0.87 in calculated in Example 5.5.

5.3.7 Conveyance Efficiency

Water can also be lost in delivering the water from its origin to the irrigation system. Losses are most significant for unlined canals, field laterals, or ditch systems that convey water over long distances through permeable soils. Water can be lost due to seepage from the canal or other conduit, by evaporation from exposed water surfaces, and by evapotranspiration from phreatophytes along the conveyance system. Water can also be lost because of operational problems in moving water through complex delivery systems. If an irrigator originally requested water delivery but later decided not to take the full supply, some water might "spill" from the system. Alternatively, a few irrigators might request water, but the canal may not be able to deliver water with such small flows. Thus, excess flow would be required to supply the requested amount.

The conveyance efficiency (E_c) is used to describe the ability of the delivery system to deliver the requested amount. The E_c is defined as the amount of water delivered to the irrigated area and applied divided by the total amount of water supplied or diverted from the supply (either reservoirs, rivers, or groundwater):

$$E_c = 100\% \left(\frac{d_a}{d_s} \right) \tag{5.19}$$

where: E_c = conveyance efficiency (%),

d_a = gross depth of irrigation water applied, and

d_s = depth of water diverted from the source.

The conveyance efficiency can be reported as either a decimal fraction or a percentage.

Measuring water losses in canals and other delivery systems is difficult and expensive, and for most management purposes, the E_c can be estimated. Several efficiency terms have been used depending on where the delivery system is located. Doorenbos and Pruitt (1977) divide the efficiency of an irrigation project into three components: supply conveyance efficiency (E_c), field canal efficiency (E_b), and field application efficiency (E_a). Conveyance efficiency and field canal efficiency are sometimes combined and called the distribution efficiency (E_d), where $E_d = E_c \times E_b$. The combination of the field canal and application efficiencies is often called the farm efficiency (E_f), where $E_f = E_a \times E_b$. Field application efficiency can be estimated from the methods described earlier in this section (e.g., Equation 5.11).

Factors affecting E_c include: the size of the irrigated area, type of schedule used to deliver water, types of crops, canal lining material, and the capabilities of the water supplies. The field canal conveyance efficiency is primarily affected by the method and control of operation, the type of soils, the canal transects, the length of the canal, and the size of the irrigated block and fields. The farm efficiency is very dependent on the operation of the supply system relative to the supply required on the farm. Doorenbos and Pruitt (1977) present approximate efficiencies for various conditions as summarized in Table 5.2.

A procedure used in the USDA-SCS *Washington State Irrigation Guide* (1985) can also be used to estimate seepage losses. The method gives a range of expected seepage losses depending on the type of material lining the delivery system and the amount of fines in the material (Figure 5.8). In addition to these guidelines, the following losses may be expected:

- Ditch side vegetation: 0.5 to 1.0% loss per mile
- Buried pipeline: 0.01 to 0.15 $ft^3/ft^2/d$ depending on the age and type of pipe.

An example calculation of the season water loss from an earthen ditch follows.

Table 5.2. Conveyance, field, and distribution efficiencies for various types of systems (adapted from Doorenbos and Pruitt, 1977).

Project Characteristics	Conveyance Efficiency
Continuous supply with no substantial change in flow	90%
Rotational supply for projects with 7,000 to 15,000 ac and rotational areas of 150 to 800 ac and effective management	80%
Rotational supply for large projects (> 25,000 ac) and small projects (< 2,500 ac) with problematic communication and less effective management:	
• based on predetermined delivery schedules	70%
• based on arranged delivery schedules	65%
Field Size and Canal Characteristics	**Field Canal Efficiency**
Irrigated blocks bigger than 50 ac with:	
• unlined canals	80%
• lined canals or pipelines	90%
Irrigated blocks smaller than 50 ac with:	
• unlined canals	70%
• lined canals or pipelines	80%
For rotational delivery systems with management and communication adequacies of:	
• adequate	65%
• sufficient	55%
• insufficient	40%
• poor	30%

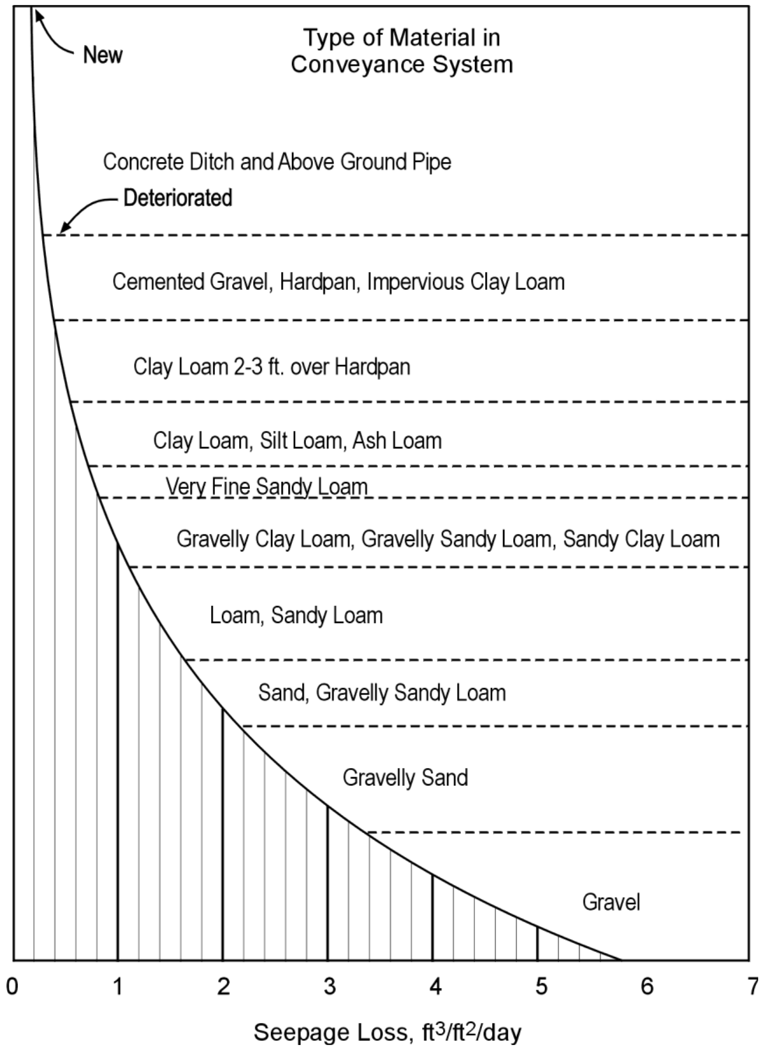


Figure 5.8. Method to estimate seepage losses from irrigation delivery systems (adapted from USDA-SCS, 1985).

Example 5.6

An unlined field ditch is 1,320 ft long, transports 2.5 cfs with a flow contact area (wetted perimeter) of 2.5 ft^2 per ft of length for 180 d/yr. The ditch traverses through loam soil.

Find: Total conveyance loss in ac-ft/yr

Solution:

Figure 5.8 shows the seepage loss of a loam soil to be about 1.4 ft^3/ft^2/d

$$\text{Seepage loss} = \frac{\text{Flow Area} \times \text{Length} \times \text{Seepage Loss Rate} \times \text{Length of Irrigation}}{43{,}560\ \text{ft}^2/\text{ac}}$$

$$\text{Seepage loss} = \frac{(2.5\ \text{ft}^2/\text{ft})\,(1{,}320\ \text{ft})\,(1.4\ \text{ft}^3/\text{ft}^2/\text{d})\,(180\ \text{d})}{43{,}560\ \text{ft}^2/\text{ac}} = 19\ \text{ac-ft}$$

Assuming vegetation loss at 1% of the total flow for the period per mile, then:

Vegetative loss =

$$\left[\left(\frac{1\%}{100\%}\right)(2.5\ \text{cfs})\left(\frac{1{,}320\ \text{ft}}{5{,}280\ \text{ft}}\right)\right] \times \left(\frac{1\ \text{ac-in/h}}{1\ \text{cfs}}\right) \times \left(\frac{24\ \text{h}}{1\ \text{d}}\right) = 0.15\ \text{ac-in/d}$$

$$0.15\ \text{ac-in/d} \times \left(\frac{1\ \text{ft}}{12\ \text{in}}\right) \times 180\ \text{d/yr} = 2.3\ \text{ac-ft}$$

Total conveyance loss = seepage loss + vegetation loss = 19 + 2.3 = 21.3 ac-ft/yr

5.4 System Evaluation

It is important to do a ***system evaluation*** at the field site regularly to check irrigation system performance. Activities for a system evaluation can be categorized into frequent and occasional activities. Occasional activities would include quantifying the irrigation application uniformity (CU or DU). Standard procedures are available, such as ANSI/ASAE S436.2 (2020) for mechanized irrigation systems. Data from the uniformity test can often be used to determine the d_z and d_e, from which the E_{LQ} can be calculated. If a pump is used in the irrigation system, the performance of the pumping plant should be checked occasionally (Martin et al., 2017). Pumps can be a significant source of energy consumption for a farming operation, so maintaining a high pump efficiency can result in cost savings. The energy requirements of pumps are discussed in detail in Chapter 8. More thorough information on occasional irrigation performance audits is presented in Thompson and Ross (2011).

Activities for frequent system evaluations include checking for flow rate, pressure (if applicable), leaks, and runoff (Heeren et al., 2020). Runoff should not be occurring (except for surface irrigation systems). For pressurized systems, check to see whether the pressure matches the design pressure. If the pressure is lower than usual, it may indicate that there is a leak in the system or that the pump is not pumping sufficient water for the current application system. If the pressure is higher than usual, there may be plugged sprinklers or emitters, or the system is set up improperly, which can increase energy costs. The flow rate should also be compared to the design flow rate. If your flow rate is lower than usual, and the pressure is lower than usual, this may indicate a problem with the well or pump. Possibilities include the screen (clogged or crusted over), declining water table, or the pump speed may be too low. For an above-ground system, binoculars or an unmanned aircraft (drone) can be used to check for leaks or plugged nozzles. Cloud-based irrigation monitoring technologies make it easier to frequently check system performance.

5.5 Irrigation System Capacity

In addition to meeting the cumulative seasonal irrigation requirement, irrigation systems must be able to supply enough water to prevent crop water stress during short time periods when plant water requirements are at their highest. The system capacity is the rate of water supply that the irrigation system must provide to prevent this water stress during peak demand. The system capacity must account for peak crop need and the efficiency of the irrigation system. The net system capacity (C_n) is determined by the supply rate needed to maintain the soil water balance above a specified level that will reduce or minimize water stress. The gross system capacity (C_g) is the combined effect of crop needs and system inefficiency. Net and gross capacity are related by the application efficiency and the percent downtime (D_t) for the system:

$$C_g = \frac{C_n}{\frac{E_{LQ}}{100\%}\left(1 - \frac{D_t}{100\%}\right)} \tag{5.20}$$

where: C_g = gross system capacity,
C_n = net system capacity,
E_{LQ} = application efficiency of low quarter (%), and
D_t = irrigation system downtime (%).

Here, system capacity can be expressed as depth per unit of time, e.g., in/d, or flow rate per unit area, e.g., gpm/ac. For the latter case gross system flow rate is determined by multiplying C_g by the irrigated area. A useful conversion is 18.86 gpm/ac = 1 in/d.

5.6 Determining System Capacity Requirements

Determining the C_n is difficult. Irrigation systems must supply enough water over prolonged periods to satisfy the difference between ET demands and rainfall. Water stored in the crop root zone can supply part of the crop demand. However, the volume of water that can be extracted from the soil should not exceed the amount that will induce crop water stress and likely yield loss. A careful accounting of the soil water status is required if stored soil water is used to supply crop water needs during periods when the crop ET demands are larger than the C_n plus any rainfall. Some irrigation designs have been developed to completely meet peak ET without reliance on either rain or stored soil water. Other techniques intentionally rely on stored soil water to meet peak crop requirements to reduce the required capacity, which decreases the initial cost of the irrigation system.

The most conservative method is to provide enough capacity to meet the maximum expected or “peak” ET rate of the crop. In this case, rain and stored soil water are not considered in selecting the C_n. This design procedure relies on determining the distribution of crop ET during the year. The ET during the season varies from year to year (USDA-SCS, 1993). With the peak ET method, the maximum daily ET for each year is determined. Then the annual maximum daily ET rates are ranked and plotted. The C_n required to meet peak daily ET 70% of the time (i.e., in 7 of 10 yr) is normally taken as the acceptable capacity when using this method.

A method to predict the daily peak period ET rate for general conditions was presented by the USDA-SCS (1970) as shown in Table 5.3. This relationship should only be used for general estimates and only if more localized peak data are not available.

Table 5.3. Peak daily crop ET rates as related to maximum monthly ET for the crop during the season and the net depth applied per irrigation (i.e., allowable depletion).

Allowable Depletion (in)	Maximum Monthly Crop Evapotranspiration (in/mo)													
	5	6	6.5	7	7.5	8	8.5	9	9.5	10	10.5	11	11.5	12
	Peak Daily Evapotranspiration (ETd) in/d													
1.0	.20	.24	.26	.28	.31	.33	.35	.37	.40	.42	.44	.46	.49	.51
1.5	.19	.23	.25	.27	.29	.32	.34	.36	.38	.41	.43	.45	.47	.50
2.0	.18	.23	.25	.27	.29	.31	.33	.35	.37	.39	.41	.44	.46	.48
2.5	.18	.22	.24	.26	.28	.30	.32	.34	.36	.39	.41	.43	.45	.47
3.0	.18	.22	.24	.26	.28	.30	.32	.34	.36	.38	.40	.42	.44	.46
3.5	.18	.21	.23	.25	.27	.29	.31	.33	.35	.37	.39	.41	.44	.46
4.0	.17	.21	.23	.25	.27	.29	.31	.33	.35	.37	.39	.41	.43	.45
4.5	.17	.21	.23	.25	.27	.29	.31	.33	.35	.37	.39	.41	.43	.45
5.0	.17	.21	.23	.25	.26	.28	.30	.32	.34	.36	.38	.40	.42	.44
5.5	.17	.21	.22	.24	.26	.28	.30	.32	.34	.36	.38	.40	.42	.44
6.0	.17	.20	.22	.24	.26	.28	.30	.32	.34	.36	.38	.40	.41	.43

The peak ET method is based on selecting a C_n that can supply water at a rate equal to the peak ET for a period. However, it is unlikely that several periods with water requirements equal to the peak ET will occur consecutively. The crop water use during the combined time period can come from the irrigation supply or from rain and stored soil water. Therefore, the capacity could be reduced if rain is likely or if stored soil water can contribute part of the ET demand.

Relying on soil water can reduce capacity requirements in two ways. First, the soil water can supply water for short periods of time when climatic demands exceed the capacity. The soil water used during the short period can be stored prior to its need or be replaced to some extent during the subsequent period when the ET demand decreases. When the C_n is less than the peak ET rate, there will be periods of shortage when crop water use must come from the soil or rain (Figure 5.9). However, during other periods, the capacity may exceed the ET and the water supplied during the surplus period can replenish some of the depleted soil water (Figure 5.9).

The second way soil water can contribute to reduced capacity requirements is through allowable depletion (AD). This is the amount of water that can be depleted from the soil before crop stress occurs. The minimum capacity that maintains soil water above the AD during critical periods of the season can be used to design the irrigation system. An example of the effect of C_g on soil water mining and the magnitude of SWD during the season are shown in Figure 5.10.

The positive bars in Figure 5.10 represent the amount of rainfall and ET during 10-d periods. After mid-May ET exceeds rain. The deficit bars represent the difference between ET and rain. The largest 10-d deficit occurs in mid-July. Without considering the use

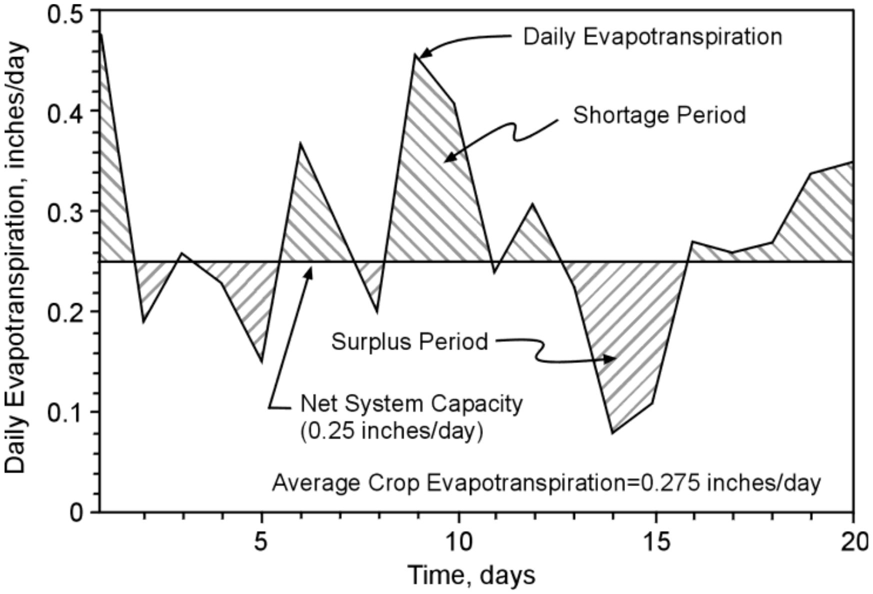


Figure 5.9. An example of the shortage and surplus periods for a system where the net system capacity is less than the average ET during a peak water use period.

of soil water, the irrigation system would have to supply all of the deficit in that period. The peak 10-d irrigation requirement would be 3.3 in per 10 d (or 6.24 gpm/ac). For the 130-ac field shown in Figure 5.10, the C_n for the peak 10-d period would be 810 gpm, and, using an 85% E_{LQ}, the C_g requirement would be approximately 950 gpm.

The amount of water that a 500 gpm capacity system, with an 85% E_{LQ} and assuming no D_t, can supply is also shown in Figure 5.10. The C_n for this system is:

$$C_n = 500 \text{ gpm} \times \frac{1 \text{ ac-in/hr}}{450 \text{ gpm}} \times \frac{24 \text{ hr}}{\text{day}} \times \frac{1}{130 \text{ ac}} \times 0.85 = 0.17 \text{ in/day}$$

The 500 gpm capacity (1.7 in/d in Figure 5.10) falls short of meeting the ET in late June and soil water would be depleted. The 500 gpm capacity continues to fall short of the 10-d deficit from early July through late August, resulting in a cumulative depletion of 4 in.

Suppose that the AD before stress occurs is 3 in for the crop and soil in Figure 5.10. With the 500 gpm capacity system the soil water would be depleted below the allowable level in late July and the crop would suffer yield reduction. Obviously, 500 gpm is inadequate for maximum yield at this site.

The C_n for a 700 gpm system is also shown in Figure 5.10. Here the system can supply the 10-d deficit for all but 20 d in late July. The cumulative soil water deficit for the 700 gpm system would be about 1.25 in with proper management. That depletion is well above the AD and should not reduce crop yield.

This example shows that the maximum cumulative soil water depletion would be approximately 4, 1.25, and 0 in for gross capacities of 500, 700, and 950 gpm, respectively. Clearly the opportunity to utilize available soil water substantially reduces the required system capacity.

Simulation programs using daily time steps to predict the soil water content have been used to determine the C_n when soil water is intentionally depleted. Some models such as by Heermann et al. (1974) and Bergsrud et al. (1982) use the soil water balance equation to predict daily soil water content. von Bernuth et al. (1984) and Howell et al. (1989) used crop simulation models to predict the C_n to maintain soil water above the specified AD or the C_n needed to maintain yields above a specified percentage of the maximum crop yield. University extension services have also created guides for determining C_n and C_g (e.g., Kranz et al., 2008).

The capacities determined using soil water and/or crop yield simulation are usually very dependent on the available water capacity (AWC) of the soil. An example from the results of Heermann et al. (1974) is shown in Figure 5.11 and is illustrated in the subsequent example problem for a sandy loam soil. To use this procedure, the

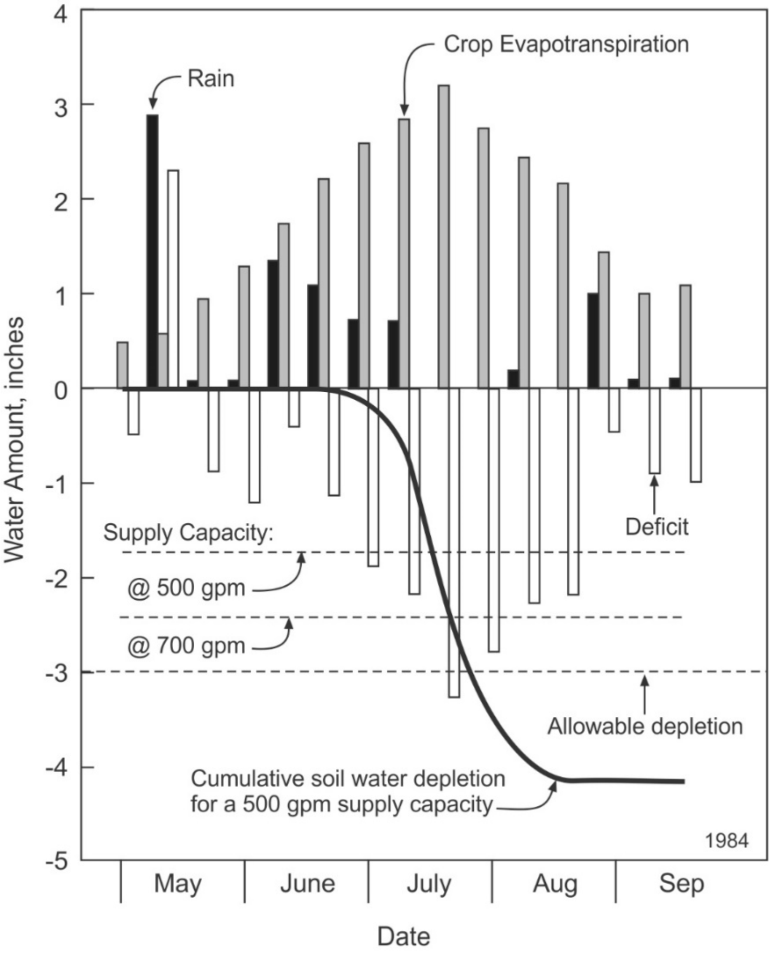


Figure 5.10. Diagram of the 10-d ET, rain and the corresponding water deficit, plus the soil water depletion pattern over a growing season as affected by gross system capacity. Based on a 130-ac field and 85% E_{LQ}.

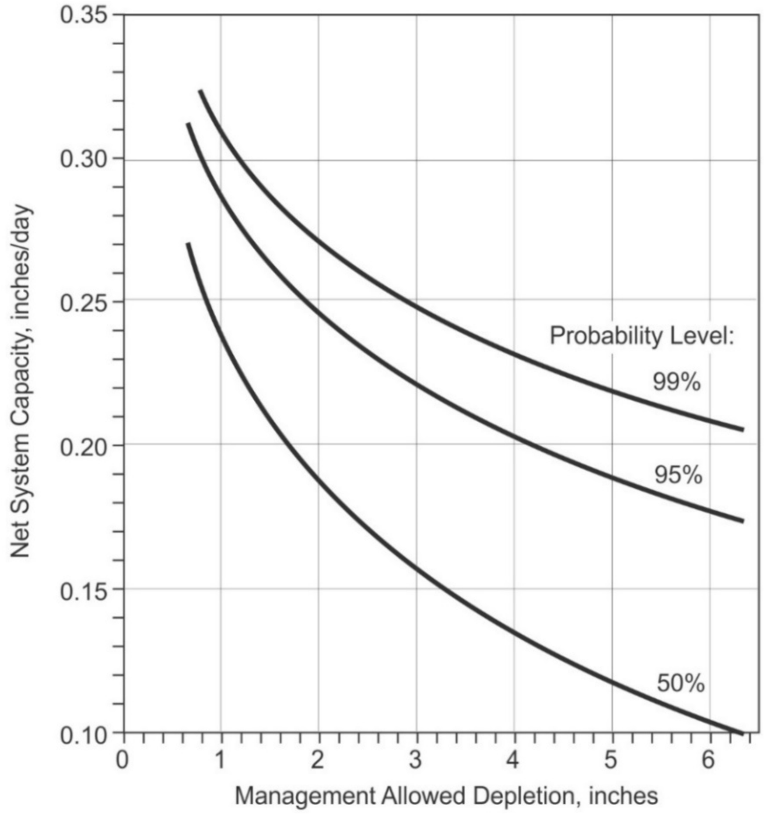


Figure 5.11. Design net capacity required for corn grown in Eastern Colorado to maintain soil water depletion above a specified depletion for 3 design probabilities (adapted from Heermann et al., 1974).

Example 5.7
Given:
A sandy loam soil that holds 1.5 in of available water per ft of soil depth.
Corn root zone depth of 4 ft.
Allowable fraction depleted = 0.50.

Find:
The net system capacity needed at a 95% probability level.

Solution:
The allowable depletion is computed as:

$$1.5 \text{ in/ft} \times 4 \text{ ft} \times 0.5 = 3.0 \text{ in}$$

From Figure 5.11, the C_n is approximately 0.22 in/d.

AD of the soil profile must be determined; the AD is the product of the allowable fraction depleted and the total AWC in the crop root zone.

The gross system capacity does not include on-farm conveyance losses. If the delivery system for the farm contains major losses, then the capacity at the delivery point on the farm should be increased. The conveyance efficiency (E_c) is used to compute the farm capacity (Q_f):

$$Q_f = \frac{Q_g}{\left(\frac{E_c}{100\%}\right)} \tag{5.21}$$

where: Q_f = farm system capacity (gpm)
Q_g = gross system capacity (gpm), and
E_c = conveyance efficiency (%).

The example below illustrates the use of the procedure to compute Q_f for two fields supplied by a network of canals (Figure 5.12).

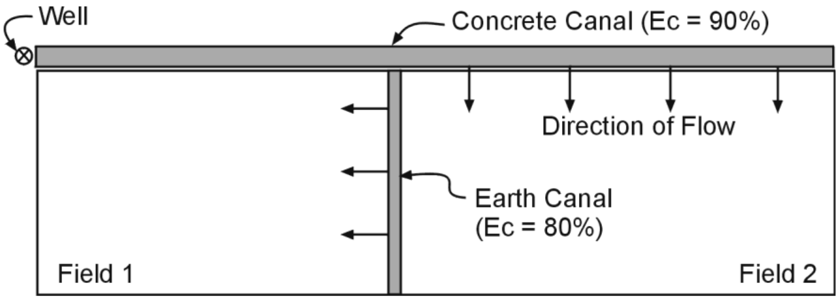


Figure 5.12. Example of a farm layout with seepage losses between the source of the water and delivery to the field.

Example 5.8

Given: A farm has an irrigation system (Figure 5.12) with a net capacity of 0.3 in/d. Each field is 80 ac, and both are furrow-irrigated with siphon tubes. The E_{LQ} is 65% for both fields. The system is shut down about 10% of the time

Find: Determine the discharge needed from the well.

Solution:

1. Net capacity for the farm is expressed in in/d, so convert to flow rate per unit area (gpm/ac):

$$C_n = 0.30 \text{ in/d} \times \frac{452 \text{ gpm}}{1 \text{ ac-in/hr}} \times \frac{1 \text{ d}}{24 \text{ hr}} = 5.7 \text{ gpm/ac}$$

2. The gross capacity for each field is:

$$C_g = \frac{5.7 \text{ gpm/ac}}{0.65\,(1 - 0.1)} = 9.7 \text{ gpm/ac}$$

3. System capacity is then:

$$Q_g = C_g \times \text{area}$$

$$Q_g = 9.7 \text{ gpm/ac} \times 80 \text{ ac} = 780 \text{ gpm}$$

4. However, the losses in the conveyance system must also be supplied by the pump.

Discharge needed for Field 1 is: $Q_{f1} = 780 \text{ gpm}/0.8 = 975 \text{ gpm}$

Discharge for Field 2 would be: $Q_{f1} = 780 \text{ gpm}/0.9 = 867 \text{ gpm}$

The well must supply the flow to each field plus the loss in the main supply canal:

$$Q_f = (975 + 867)/0.9 = 2{,}047 \text{ gpm, or about } 2{,}050 \text{ gpm}$$

5.7 Operational Factors

An irrigated area is often subdivided into tracts of land called sets or stations. A ***set*** or ***station*** is the smallest subdivision of the total area that can be irrigated separately. The term set is often used for agricultural systems. The set is the area of the field that is irrigated at one time or by a terminal section of the delivery system. For example, for a moved lateral sprinkler system, the land area irrigated while the lateral is stationary would be a set. The block of furrows supplied water at one time would be a set for a furrow system. In landscape and turf applications, the total area is divided into stations. The term "station" comes from the use of controllers that have "stations." The plumbing of the sprinkler or microirrigation systems is such that the station is irrigated at one time. The size of the stations may vary considerably depending on the geometry of the landscape.

The length of time that water is applied to a set is called the ***application time***. The time between starting successive sets in the field is called the ***set time***. The application time and the set time may be the same if the irrigation system is not stopped to change sets. Some systems require that the laterals drain before they are moved. Then the set time is longer than the actual application time. To apply the desired depth of water the application time must be correct. For automated systems the set time can vary for each set or station depending on the water requirement. For manually moved systems the set time may be less flexible. It is common that the set time is adjusted to fit the labor schedule. For example, a 12-h set time is very common for furrow or moved lateral sprinkler systems even though less water may be required at certain times of the season. An inflexible set time can lead to over irrigation and deep percolation if adjustments in flow rate are not made.

The amount of time between starting successive irrigations is called the ***cycle time*** or ***irrigation interval***. For example, suppose a furrow irrigated field is irrigated once per week. The cycle time would be 7 d. The time during the irrigation interval that the irrigation system is not operated is called the ***idle time***. Suppose that the furrow field just mentioned could be irrigated in 5 d. The idle time would then be 2 d. Idle time is very similar to the downtime used to determine system capacity. They would be the same if the application time and the set time are the same. If some time is needed to change sets, then the downtime will be larger than the idle time.

When systems are supplied by an irrigation district, you will often hear the terms duration and rotation used. The ***duration*** is the time that water is provided to the farm. The ***rotation*** is time between the start of times when the water is provided. If the whole field is irrigated each time water is provided, the rotation time is the same as the cycle time. For example, an irrigator might receive water for 4 consecutive days and then be without water for 10 d. In this case, the duration would be 4 d and the rotation would be 14 d.

5.8 System Characteristics

Characteristics of irrigation systems are listed in Table 5.4. The values listed in this guide are average quantities for the respective systems. The table is useful in the preliminary stages of developing and managing irrigation systems. The actual value of the various parameters can vary considerably depending on both design and management.

There has been much written and said about the selection of irrigation systems to fit specific properties of a site. Some factors affecting the selection of a water application method are listed in Table 5.5. The reader should consider these criteria to be general. Since this text deals with managing irrigation systems, it is important to operate the system as efficiently as possible. The practitioner will find that many systems have been installed and operated quite economically even though they do not conform to traditionally defined limits on the irrigation method. An *Irrigation Consumer Bill of Rights*™ has been developed which provides several questions to ask when discussing the selection of an irrigation system with a dealer (ITRC, 2019).

Table 5.4. Typical characteristics of various irrigation systems.

System Type	Maximum Slope (%)	Pressure Required (psi)	Labor Required (hr/ac/irrig)	E_{LQ} (%)	Nominal Application Depth (in)
Surface:					
Furrow gated pipe without reuse	2	0.5–10	0.5–1.0	40–70	2.0–6.0
Furrow gated pipe with reuse	2	0.5–10	0.5–1.0	60–85	2.0–6.0
Furrow siphon tube	2	0	1.0–1.5	35–65	2.0–6.0
Graded border	2–4	0–10	0.2–1.0	50–85	1.5–6.0
Level basin	0	0–10	0.05–0.5	70–85	1.5–6.0
Sprinkler:					
Hand move	20	50–70	0.5–1.5	60–80	1.0–6.0
Solid-set	No limit	50–70	0.05–0.1	60–85	0.5–4.0
Side roll & towline	10	50–70	0.1–0.3	60–80	1.0–6.0
Boom	5	60–80	0.2–0.5	55–75	1.5–4.0
Traveler	5–15	70–100	0.1–0.3	55–75	1.5–4.0
Center pivot	10–20	20–70	0.05–0.15	75–90	0.25–2.0
Pivot with corner system	10–20	30–70	0.05–0.2	70–85	0.25–2.0
Linear move	5–8	20–50	0.1–0.3	75–90	0.2–2.5
Micro, drip, trickle:					
Point source	No limit	20–50	0.05–0.2	70–90	Small
Lateral (continuous) source	No limit	20–50	0.05–0.2	70–90	Small

Table 5.5. Factors affecting the selection of a water application method.

Water Application Method	Factors Affecting Selection			
	Land Slope	Water Intake Rate of Soil	Water Tolerance of Crop	Wind Action
Sprinkler	Adaptable to both level and sloping ground surfaces.	Adaptable to any soil intake rate.	Adaptable to most crops. Typical systems may promote fungi and disease on foliage and fruit.	Wind may affect application efficiency and uniformity.
Surface	Land area must be leveled or graded to slopes less than 2% for most systems. It issometimes possible to flood steeper slopes that are sodded.	Not recommended for soils with high intake rates of more than 2.5 in/hr or with extremely low intake rates such as peats or mucks.	Adaptable to most crops. May be harmful to root crops and to plants which cannot tolerate water standing on roots.	No effects.
Trickle/drip micro	Adaptable to all land slopes.	Adaptable to any soil intake rate.	No problems.	No effects.
Subsurface drip irrigation	Adaptable to all land slopes.	Best adapted to medium and fine-textured soils with moderate to good capillary movement.	Adaptable to most crops. Saline water tables limit application.	No effects.
Below surface subirrigation	Land area must be level or contoured.	Adaptable only to soils which have an impervious layer below the root zone, or a high, controllable water table.	Adaptable to most crops. Saline water tables limit application.	No effects.

5.9 Safety with Irrigation Systems

Irrigation systems can pose several potential hazards, so safety should always be a priority. Hazards from mechanized irrigation systems include missing driveshaft covers, possible falls from ladders and towers, numerous moving parts, and lightning. Drowning is a concern with canals and water storage ponds. Some micro and sprinkler irrigation systems are used to apply chemicals which can be toxic. A very important safety concern is electrical safety, since many irrigation systems use a high voltage (480 V) power supply to pump water and/or to run motors which move the system. The combination of metal structure and wet environment results in a risk of electrocution. Irrigation managers should always be cautious when working or irrigating near overhead power lines. It is the responsibility of producers, service technicians, and others working around irrigation systems to be aware of hazards and safety practices. Anyone designing or constructing an irrigation system must follow the applicable laws, codes, and engineering standards. More thorough information on electrical safety related to irrigation systems is presented in ANSI/ASAE S397.4 (2018), ANSI/ASAE S362.2 (2014), Nolletti (2011), and Marek and Porter (2018).

5.10 Irrigation Efficiency and Water Resources Sustainability

The performance measures discussed in Section 5.3 are all related to the more general term irrigation efficiency. Irrigation efficiency is the ratio of the irrigation water that is beneficially used to the depth of water applied or delivered. Irrigation technologies that improve irrigation efficiency can reduce pumping and the associated energy costs, and in some cases can reduce labor. Reduced pumping often improves the water quality of water resources: reduced deep percolation reduces the leaching of nitrates and other solutes from the root zone to aquifers, and reduced runoff reduces the transport of sediment, nutrients, and pesticides to surface water bodies.

Often it is incorrectly assumed that ***water conservation*** at the watershed scale will automatically follow an improvement in irrigation efficiency at the farm scale. Whether or not liquid water is actually conserved depends upon what led to improved irrigation efficiency in the first place. If efficiency is increased by reducing evaporative losses, liquid water will certainly be conserved. However, if efficiency is improved by reducing deep percolation in a groundwater irrigated region, water may not be conserved since the percolating water may recharge the aquifer from where it originated. In that case, the water is simply being recycled. While the deep percolation could be causing water quality degradation and increased energy expenditures, reducing deep percolation to increase irrigation efficiency may not actually conserve liquid water. A similar example can be developed for surface runoff of irrigation water. Downstream irrigators often depend on the water “losses” or waste from upstream irrigators. A good discussion of this topic is presented by CAST (1988).

Hydrological conservation is needed when water must be conserved to sustain a fresh water supply or to meet a downstream demand for fresh water. From a watershed-scale perspective, “consumptive use” is a helpful concept. ***Consumptive use*** is defined as water that is diverted for use and is not returned to the water resource system. A coal power plant that diverts stream water for cooling returns that water to the stream; this is not a consumptive use and the water is available to downstream users. In agricultural watersheds, the largest consumptive use of water is ET. For example, over long time scales, if groundwater levels remain constant, outflow from a watershed is approximately equal to the difference between the precipitation and ET (Figure 5.13). To reduce aquifer depletion and/or increase stream flow, consumptive use must be decreased. In some situations, water allocations may be required to reduce yield-producing ET. Many irrigation technologies help at the farm scale and help with water quality but don’t reduce consumptive use (Grafton et al., 2018).

Since the term irrigation efficiency does not identify the disposition of unused water, Perry et al. (2009) encourage the use of alternative terms when hydrological conservation, not irrigation system performance, is the consideration. Key terms that they suggest are consumed fraction, recoverable fraction, and non-recoverable fraction. The ***consumed fraction*** includes both beneficial consumptive use (transpiration resulting in yield) and non-beneficial consumptive use (soil evaporation, transpiration from weeds). The ***recoverable fraction*** is water

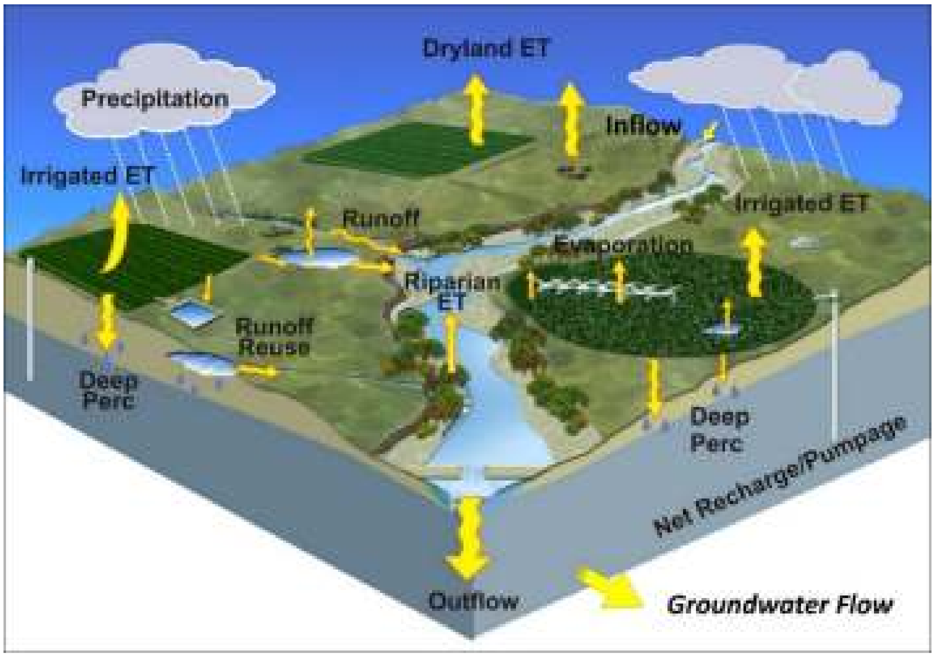


Figure 5.13. Watershed-scale water balance.

that can be reused, such as deep percolation to an aquifer or return flows to a river. The ***non-recoverable fraction*** is not consumed but also is not available for further use, e.g., water that drains from an irrigated region into a saline system, or deep percolation to a very deep aquifer (from which it is too expensive to pump the water). Watershed-scale conservation programs should target reduction of the consumed fraction and/or the non-recoverable fraction.

5.11 Summary

Irrigation systems can be classified into three general categories: Surface, sprinkler, and micro. While the characteristics of each of these systems differ, none of them apply water perfectly to an irrigated area. Water is never uniformly distributed across the land, and some water goes to evaporation, runoff and deep percolation rather than being used by plants. Common terms can be used to describe how efficiently irrigation systems apply water. Distribution uniformity (DU) and Christiansen's Uniformity Coefficient (CU) are used as indices of water application uniformity. Application efficiency (E_a) and application efficiency of the low-quarter (E_{LQ}) are used to describe what proportion of the applied water is stored in the soil and available to plants.

Deep percolation is an important loss in irrigation because, not only does it result in larger applications of water than needed, but also chemicals can be leached with the percolating water. The amount of chemical leaching loss can be quantified by knowing the deep percolation losses and the concentration of the chemical in the leachate.

Water can also be lost to seepage and evaporation during conveyance. Seepage losses can be significant in unlined ditches and canals. It is important to consider losses at both the field scale and the watershed scale. Irrigation technologies that increase application efficiency often do not conserve water at the watershed scale, particularly if the technology does not reduce consumptive use of water.

The amount of water needed to meet irrigation needs is called the system capacity requirement. System capacity is determined by knowing land area, plant needs, E_{LQ}, and downtime or system operation time.

Questions

1. Consider a sprinkler-irrigated sports field where the depth of water applied from the original source is 0.90 in, the soil water deficit (SWD) prior to irrigation is 0.8 in and the depth of water lost to runoff, evaporation, and drift is 0.05 in. Determine the application efficiency of the low-quarter (E_{LQ}) for the following three conditions: (a) the infiltrated water is perfectly uniform, (b) the average depth of water infiltrating in the low quarter of the field is 0.70 in, and (c) the average depth of water infiltrating the lowest quarter of the turf area is 0.80 in.
2. For the three conditions described in Question 1, calculate the distribution uniformity (DU).
3. If you had sufficient funds and were irrigating an apple orchard, which irrigation system would you choose and why? If funds were limited and the apple orchard was nearly level, which system would you select? Why?
4. Which irrigation system would you install in your area to irrigate a golf course? Why?
5. If a turf field needs 1.2 in of water, the scheduling coefficient is 1.25, and the sprinkler system applies 0.5 in/hr, how many hours of irrigation are required to be sure that 90% of it is adequately irrigated?

6. Calculate the distribution uniformity and Christiansen's coefficient of uniformity for a lateral move sprinkler system with the depths of water collected in the following 16 catch can containers.

Can No.	Depth (in)	Can No.	Depth (in)	Can No.	Depth (in)
1	1.2	7	1.4	13	1.0
2	1.1	8	0.8	14	0.9
3	1.3	9	0.7	15	0.9
4	0.9	10	0.9	16	1.2
5	1.0	11	0.9		
6	1.0	12	0.8		

7. If one million gallons of water are applied to three holes of a golf course and 0.8 million gallons of this application are stored in the root zone, what is the application efficiency?

8. Calculate Christiansen's coefficient of uniformity for a center pivot system with the following catch can container data.

Water Depth in Can (in)		
Distance from Pivot Point (ft)	Radial Line #1	Radial Line #2
15	0.9	1.0
30	1.0	1.0
45	1.1	1.1
60	0.8	1.0
75	1.0	0.9
90	1.0	0.9
105	1.0	1.0
120	0.9	1.0
135	1.0	1.0
150	1.0	1.0
165	1.1	1.1
180	1.0	1.0
195	0.9	1.0
210	1.1	1.1
225	0.9	0.9
240	0.9	0.9
255	1.1	1.0
270	1.0	1.0
285	0.9	0.9
300	1.0	

9. If an irrigation system has a distribution uniformity of 0.85 and a total depth of 2.0 in was applied, d_z equaled 1.9 in, and the SWD was 1.7 in, determine the system's loss of water due to evaporation, drift, and runoff.

10. Calculate the annual seepage loss for a new concrete-lined ditch that is 10 miles long, carries water for 200 d each year, and has a flow area of 3 ft^2/ft. Report your answer in ac-ft/yr.

11. Determine the gross system capacity (Q_g) for a golf course if the application efficiency for the low-quarter is 75%, the system is inoperable no more than 10% of the time, and the net system capacity is 20 million gal/d.

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